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Metallurgical Project

A. H. Compton, Project Director

* * * *

Clinton Laboratories

M. D. Whitaker, Director

R. L. Doan, Associate Director for Research

* * * *

PHYSICS RESEARCH

H. W. Newson, Section Chief

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Physics of the Clinton Pile

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March 6, 1944

This work was done under problem assignments 100-X1P, 103-X2P, and 133-X3P.

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Table of Contents

Note: Tables and figures are numbered from one in each section of this report.

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Abstract

It is the purpose of this report to present the results, insofar as is possible, of the physics research that has been done on the Clinton Pile. The size of the pile has been determined and the critical Laplacian is given as approximately -102×10^{-6}. The comparison between the integration of long period reactivity measurements and reactivity determinations by means of short periods and the inhour formula indicates that the formula gives values 20% low.

Temperature coefficients for the pile as a whole, for the metal, and for graphite are summarized in Table III of Section III. If allowance is made for the change of density of air with temperature, graphite shows an unexplained negative temperature coefficient. The coefficient for the metal is larger than the reported Doppler effect measurements indicate.

Preliminary results based on a method of calibrating the pile while it is at operating equilibrium are given in Section IV.

Accurate calibrations of the regulating rods are reported in Section V. These have been obtained by determining the amount of motion necessary to compensate for the introduction of a small cadmium strip while maintaining the temperature of the pile accurately constant. Measurements of the ripple due to the metal absorption and of the effect of poisoning are also reported in this section. The coordinate system used is described in the appendix.

A development of appropriate counting foils and neutron flux measurements made with them are reported in Section VI.

The activity in the cooling air is about 5×10^{-11} curies per cc due to the active argon and an approximately equal amount due to fission products. The origin of the fission products has not yet been definitely determined. It has also been found that about one-half of the active argon is retained in the graphite and diffuse out slowly. The total amount of argon activated is in close agreement with that to be expected.

WRK

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Section I

The Change of the Period of the Pile with Loading

Problem Assignment No. 100X1P

In CP-1081 the loading and the monitoring of the pile was described. The most interesting point involved had to do with the change in period of the pile as metal was added beyond the critical loading. This data was tabulated in that report and a part of it will be reconsidered here in the light of later experience.

In the first loading after critical for which measurement was taken there were 369 filled channels. However, three channels near the center of the lattice were empty. From later measurements described in CP-1173 it was found that the removal of a central rod caused a loss of approximately 22 ih. From the loading data it was found that an addition of one rod on the outside of the lattice caused an increase of 3.9 ih on the average. The weight factor between the two is, therefore, 5.6. The intensity relative to the center of one of the rods was .98 and the square of this is .96. The other two rods were the same distance from center. Their intensity factor is .77 and its square is .6. The three empty channels are, therefore, equivalent to 5.6x (.96+2x.6) = 12. Consequently, if the three empty channels had been filled 12 channels could have been removed from the outside of the lattice without changing the reactivity of the pile. In Table 1 this correction is shown as the second column where nine rods have been subtracted from the actual number. In order to calculate the radius of the active lattice the number of rods is multiplied by the area of the graphite surrounding each rod, which is one square lattice unit or 64 sq in. The radius equivalent to this area is found and is then increased by the augmentation distance ℓ which is of the order of magnitude of the diffusion length of neutrons in the graphite. Reflector theory does not appear able at the present time to state the proper value of ℓ exactly. However, it should be between 42.5 and 50 cm for our graphite which had a diffusion length about 50 cm.

Our experimental attempts to determine the effective radius of the lattice seemed to indicate a somewhat larger augmentation distance. For this reason, calculations are made on the basis of $\ell = 42.5, 50, 57\frac{1}{2}$ cm. $\Delta_I = 2.4^2/r^2$ is tabulated for each value of ℓ and for the various loadings for which period measurements are available. These values are sufficiently close together that the proper value may be found by interpolation when a definite decision can be made on the value of ℓ. The period in seconds corresponding to each of the loadings is given in the sixth column. The seventh column shows reactivity of the pile in inhours as calculated from the formula

$$\left(\Delta ih = \frac{64}{T} + \frac{245}{T+3.6} + \frac{688}{T+10} + \frac{1938}{T+35} + \frac{665}{T+83}\right)$$

Table I

Number of filled channels	Corrected number	$\ell = 42.5$ $-\Delta \times 10^{-6}$ cm^{-2}	$\ell = 50$ $-\Delta \times 10^{-6}$ cm^{-2}	$\ell = 57.5$ $-\Delta \times 10^{-6}$ cm^{-2}	T sec	ih From Short Period Measurements	ih By Integral Methods
369	360	85.4779	80.7529	76.4030	126	23	30
373	364	84.6911	80.0030	75.7428	62.0	39	50
377	368	83.9192	79.3205	75.0897	35.5	56	70
381	372	83.1621	78.6246	74.4486	22.1	74	90
385	376	82.4190	77.9414	73.8191	16.7	36	104
389	380	81.6898	77.2707	73.2007	11.9	100.8	121
$-\Delta_{\perp}$ Critical		86.575	81.750	77.425			
$-\Delta$ Critical		105.019	100.194	95.869			
$\frac{(\Delta_{c})}{\delta ih}$	(period) (integration)	4.75×10^{-8} 3.80	4.35×10^{-8} 3.48	4.2×10^{-8} 3.36			
$\frac{\delta K}{\delta(ih)}$	(period)	3.23×10^{-5}	2.95×10^{-5}	2.85×10^{-5}			
$\frac{\delta K}{\delta(ih)}$	(integration)	2.58	2.36	2.27			

$$h_{metal} = 677.5 \text{ cm}$$

$$h = 731.5 \text{ cm}$$

$$\frac{\pi^2}{h^2} = 18.44 \times 10^{-6} \text{ cm}^{-2}$$

In the last column of the table the reactivity in inhours as found by Haydn Jones' control rod calibrations is shown. As explained in Section V these measurements indicate that the above formula gives the value for the inhours which is 20% low. This seems to be a nearly constant factor in the range of periods in which we are interested.

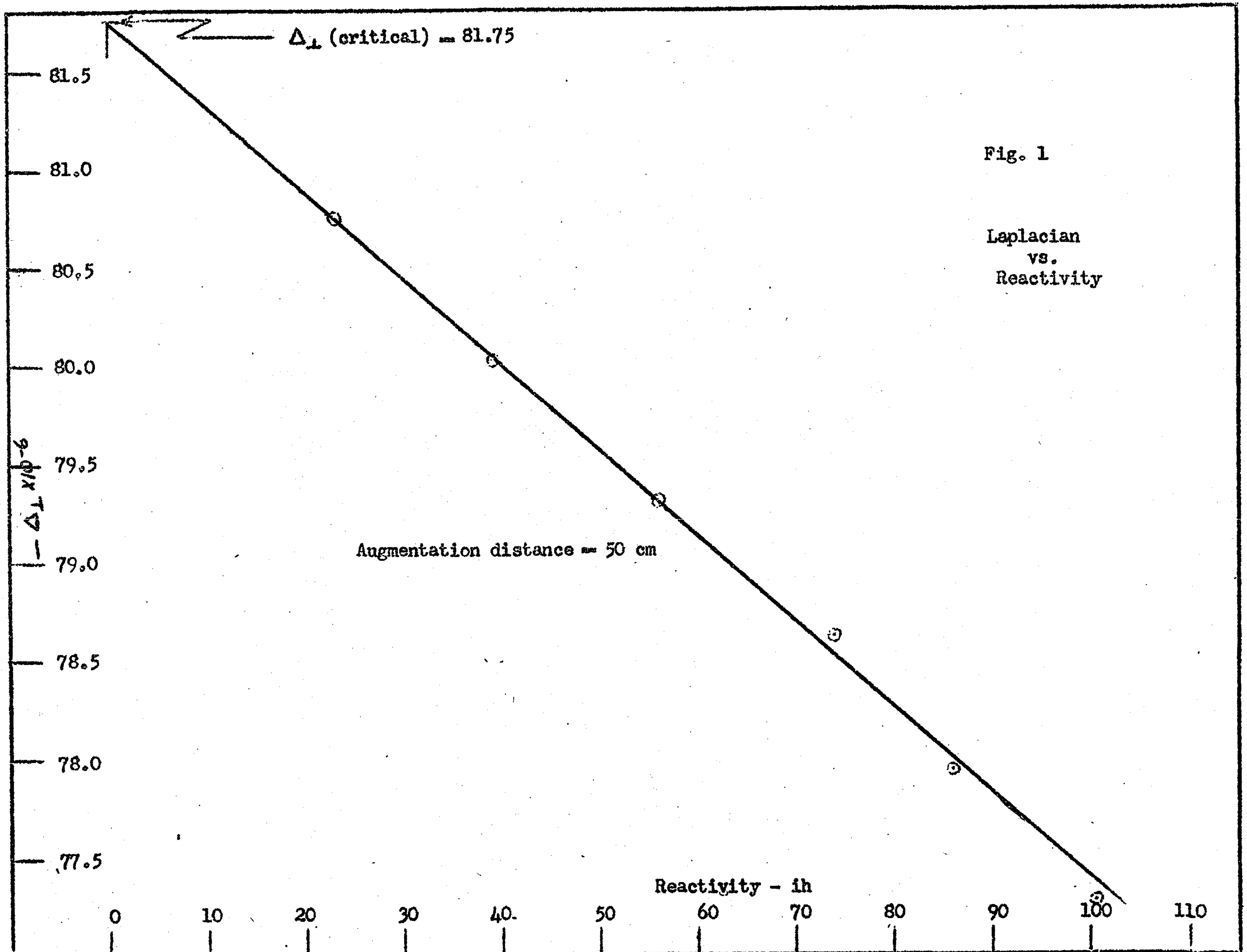
The inhour figures in column 7 are plotted against the values of the Laplacian for the augmentation distance 50 cm as shown in Figure 1. The points farthest to the right on the curve correspond to rather short periods which are difficult to measure and the agreement of the points with a straight line is within the reproducibility of the measurements. This is also true for plots using the other augmentation distances. From the slope of the curve we can obtain the change of the Laplacian with the change in inhours. These are shown in the lower part of Table 1 for both of the sets of inhour units used in the table. In order to convert this to the change in k it is necessary to assign the value of the migration area. This number is rather difficult to determine and the value of 680 cm^{+2} has been selected. A spread of about 7% on each side of this value will include estimates for this figure based on various methods of treating the same data.

The most probable value for the change of k to inhours is 3.0×10^{5} if we use the inhour calibration calculated from the short period measurements and 2.4×10^{-5} if we take the value which is based on long period measurements. The latter figure seems much more reliable and is in agreement with information privately communicated by Mr. Fermi who has altered the inhour formula with the use of later measurements of the decay of the delayed neutrons.

To determine the critical value of the Laplacian it is necessary to assign an effective height to the cylindrical pile. The actual length of metal in the pile is 677.5 cm. The augmentation distance is less important here since the contribution to the Laplacian is small. It has been decided to add 10 cm to the length of the pile on one end where the metal and the graphite are approximately flush and 44 cm at the other end where a considerable reflector is present. This gives an answer of 731.5 cm which is exactly the length of the graphite in the pile. This gives the parallel contribution to the Laplacian,

$$\frac{\pi^2}{h^2} = 18.44 \times 10^{-6}$$

If this is added to the critical value for the transverse component, the critical Laplacian of the pile becomes 105, 100, or 96 for the different augmentation distances. The most probable value at present is approximately 102; Inasmuch as the experimental attempts to determine the radius have been somewhat disappointing and the smaller figure cannot be considered as established.


$\Delta_{\perp}$ (critical) = 81.75
Fig. 1
Laplacian
vs.
Reactivity
Augmentation distance = 50 cm
$\Delta_{\perp}$ x10-6
81.5
81.0
80.5
80.0
79.5
79.0
78.5
78.0
77.5
Reactivity - ih
0
10
20
30
40
50
60
70
80
90
100
110

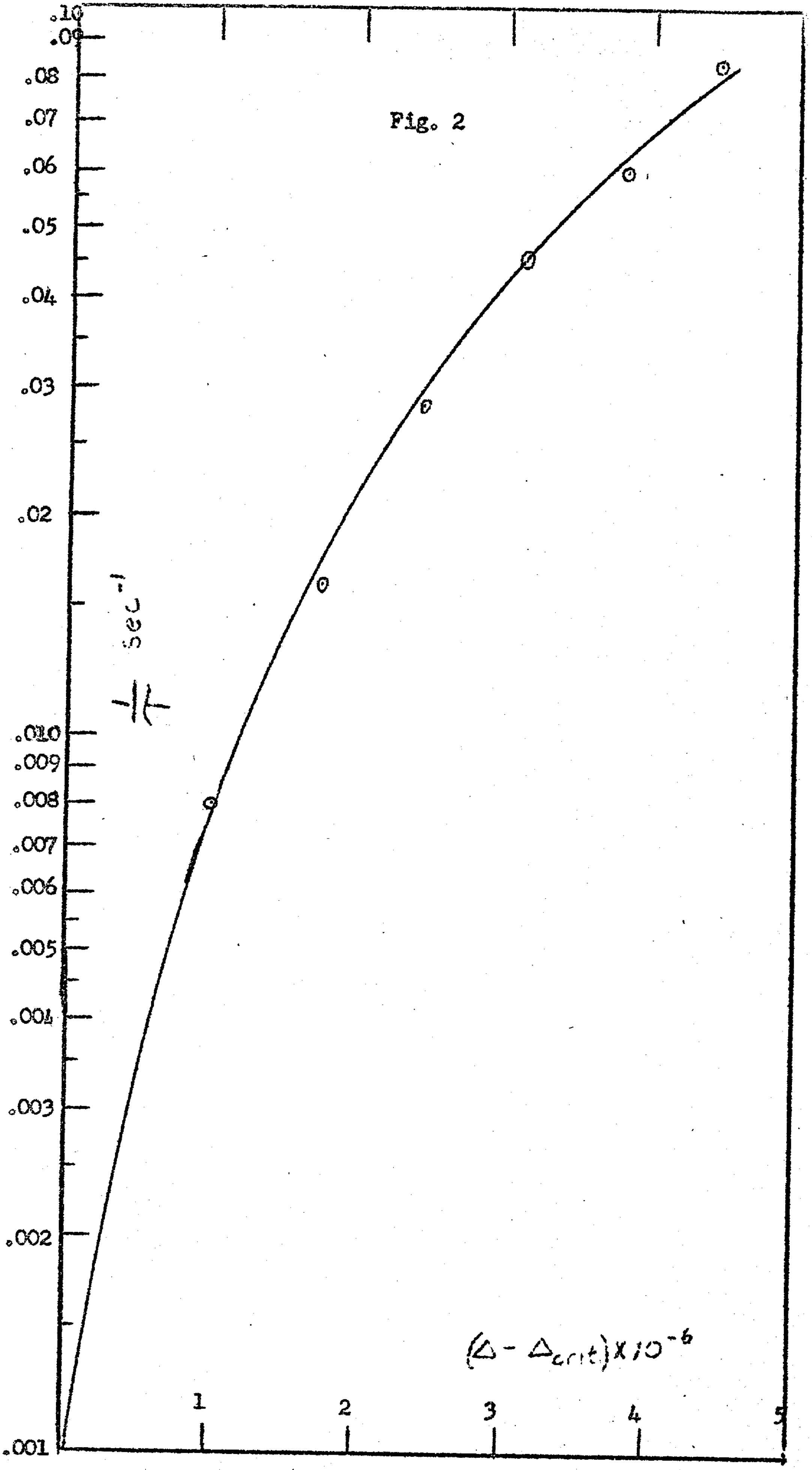


Fig. 2
.10
.09
.08
.07
.06
.05
.04
.03
.02
.010
.009
.008
.007
.006
.005
.004
.003
.002
.001
$\frac{1}{T}$ sec^{-1}
1
2
3
4
5
$(\Delta - \Delta_{crit}) \times 10^{-6}$

It has been suggested by Mr. Wheeler that it might be well to give up the concept of the inhour unit and make calibrations on the basis of the comparison of Laplacian with the period of the pile. However, a plot of our data is shown in Figure 2 and it is seen that a much more extensive set of measurements would have to be made in order to be able to interpolate the rather complicated curve. Moreover, as is seen here, there is some question as to the exact value of the Laplacian, whereas the inhour is defined in a definite experimental basis providing the calibrations are based on periods of the order of an hour. Furthermore, experiments of this kind can only be performed on occasions when a new pile is being built and the opportunity for checking the data is rather meager.

The results of the new calibration were only available after a considerable quantity of this report had been written. We have also published a considerable number of preliminary results based on the older calibrations. It will, therefore, be necessary in this report to discuss the inhour determinations on the basis of the several standardizations. Furthermore, our data has not been taken over a sufficient range to attempt to set up a new inhour formula and our corrections, consequently, apply only over a limited range of periods. We are rather confident that the calibrations made by Jones are substantially correct.

II. Temperature Measurements and Power Calibration

Problem Assignment No. 100X1P

A considerable number of temperature measurements have been made at various points and conditions of the pile. Most of this data has been given in CP-1081 and 1173. The data are so complicated that there seems to be no feasible way to present it in a unified form. Some of this data has been used by Leverett and Lane (CE-1200) to calculate the thermal conductivity of the graphite. There is much more data available, but in general it has only been worked up with some specific use in mind.

Mr. Kanne has attempted to measure the energy due to the radioactivity of the lumps by observing their temperature immediately after the pile has been shut down. This has been surprisingly difficult to detect considering that there should be/temperature corresponding to 5-10% of the operating power. Further experiments are in progress. A power calibration was performed by Mr. Fermi at the time of start-up and is reported in CP-1081. Nothing further has been done with this type of measurement. However, Mr. Leverett's section has calibrated the venturi tube. Both Leverett and the operating group have measured the power from the increase in temperature of the air and find the previous power calibration low by about 10%. This discrepancy is probably not due to the errors in either measurement but due to the fact that the ionization chambers have been shifted several times since Fermi's calibration and also to the fact that the control rod pattern has a considerable effect on the galvanometer reading for the same power output.

In CP-1081 it was stated that the neutron flux per watt at the center of the pile was 6.5×10^5. A calculation of a theoretical prediction was also stated to be in agreement with this figure. However, it has since been found that the calculation is in error and a study of the flux measurements which were made at that time showed them to be lacking in consistency. We now use the figure 4.0×10^5 neutrons/sec/cm^2/watt as the flux at the center of the pile. This is the correct theoretical prediction. Techniques are being developed to compare the flux in the pile with a standard Ra-Be source. However, this requires a comparison of the order of a factor of a million and the experiments have not so far been successful.

Section III

The Temperature Coefficient of the Clinton Pile

Problem Assignment No. 103X2P
H. W. Newson, W. R. Kanne

NOTE: The following temperature coefficients were measured with control rods which had been calibrated by measuring several short pile periods for various displacements of the rods. These were converted into inhours by the use of the empirical formula as discussed elsewhere; there is reason to suppose that this formula gives results which are low by 20%. The low values are used throughout this section of the report. They have also been reported from time to time in previous reports. The table at the end of the report summarizes the data with both sets of units. The higher set of units is probably the more accurate.

The Practical Temperature Coefficient

A number of experiments have been performed in an attempt to determine the temperature coefficient of the Clinton pile under various conditions. The simplest of these, which we call the practical coefficient, is the change of reactivity of the pile compared to the temperature of a metal slug, which we believe to be the hottest in the pile. This coefficient is affected by temperature gradients in the pile. The gradients will be effected both by the temperature of the cooling air and by the volume of the air. However, we have obtained consistent results under all actual operating conditions so far. Table 1 shows an experiment of this kind in which the pile was brought to temperature equilibrium at several values of the power output. Inasmuch as the displacement of three control rods is involved, the accuracy of the measurement suffers because there are rather serious shadowing effects between the various rods. However, the final figure* of about $\alpha'_p = -0.58$ ih/C° is useful in computing the loss of reactivity from room temperature to the operating temperature of the hottest slug, and seems to be reasonably consistent with our other experiments.

The Total Temperature Coefficient

We have made a single measurement of the change of reactivity of the pile when the temperature was practically uniform throughout the pile in both the initial and final states.

*α' means a temperature coefficient based on our arbitrary temperature without correcting for a non-uniform temperature distribution. α implies a coefficient for a uniform temperature change. The subscripts M, G, and T indicate whether the change occurs in graphite, metal or both. The subscript p indicates the practical coefficient.

This experiment was performed by heating the pile with steam radiators which were installed in the inlet air chamber. Before the experiment started there had been no air circulation for some days and the temperature of the active portion of the pile was quite uniform. The temperature was measured with a thermohm at the center of

Table I

Power kw	Change in Metal Temperature Near Maximum	Loss in Reactivity ih	Temp. Coeff. $-\alpha_p$ ih/°C
100 °C	46-12	21	.62
400 °C	123-12	62.2	.56
600 °C	151-12	79	.57
		Average.....	.58

the graphite structure. The resistance of the thermohm was initially 97.32 ohms, corresponding to a temperature of 11.0° C. After the pile had been heated, the resistance of the central thermohm was 102.2 ohms, corresponding to a temperature 25.0° C, or a net increase of 14.0° C. The critical position of the control rod initially was 105.85". The pressure was 746.6 mm. In the final condition the critical position of the control rod was 111.66" and the pressure was 750.6mm The sensitivity of the control rod in this region was 1.98 ih/". The reactivity of the pile then decreased by $-5.81" \times 1.98 = -11.5$ ih. This must be corrected for a pressure change of 4 mm which amounts to 1 ih, and the net change in ih, therefore, is $-11.5 + 1.0 = -10.5$ ih. This gives a coefficient of $\alpha_t = -.75$ ih/°C. The final temperature distribution was uniform radially, but a certain amount of gradient was present longitudinally. However, these longitudinal gradients are sufficiently close to linear to cause no particular error in using the central temperature as a uniform temperature.

The Metal Temperature Coefficient

Our most promising method for determining the metal temperature coefficient when the temperature of the graphite is held constant is obtained by allowing the pile to come into equilibrium with the cooling air at the operating power. Very satisfactory critical positions may be determined under these conditions. The pile is then shut off but the fans continue in operation and the temperature of the metal drops below the temperature of the graphite. The critical position is measured under this condition with a very small power output. If these measurements are made reasonably rapidly, there is very little change in the graphite temperature.

Table II shows three experiments of this kind. In the first two, the fans were left on during the whole experiment. In the third the fans were shut off after the critical position was determined and the critical position was measured again. The inhour change as shown is corrected for the pressure change of 11.0 mm. In the average the third experiment was considered much the best of the three and was weighted double.

Table II

Metal Temperature Near Maximum	Temperature after shut down	Loss in reactivity (ih)	α'_m	α_m ih/°C
150°C	64°C	35	-.407	-.63
151°C	55°C	39.4	-.410	-.68
150°C	69°C	37	-.457	-.76
(Fans off, same expt)	76°C	34	-.460	-.77
		Average	-.43	-.72

If α' is the practical temperature coefficient α'_m, that of the metal alone? and α'_t that of metal and graphite at the same temperature they are related as follows:

$$\alpha'_p\,(T_2 - T_o) = \alpha'_m\,(T_2 - T_1) + \alpha'_T\,(T_1 - T_o)$$

$$\alpha'_T = \frac{.58\,(150^o - 12^o) - .43\,(150 - 76)}{76 - 12^o}$$

$$\alpha'_T = -.75 \text{ inhours}/^oC$$

Where T_o is the temperature of the pile before start-up, T_1 is the central graphite temperature at running conditions, and T_2 is the operating metal temperature in the center. The α''s are temperature coefficients calculated from the central metal temperature where there is a non-uniform temperature distribution.

α'_m may be corrected to α_m by the fact that $T_2 - T_1$ is approximately proportional to the neutron flux throughout the pile. Then for each cell in the pile

$$\delta T_1 = (T_2 - T_1)\, N_i/n\,(\text{center})$$

and for each cell in the pile the loss in k is proportional to the square of the neutron density

$$\delta k_1 = \alpha\,\delta T_1\,\frac{N^2}{\eta^2}\,i = \alpha(T_2 - T_1)\,\frac{N^3}{\eta^3}\,i = \alpha(T_2 - T_1)\left[\cos\frac{\pi x}{2a}J_o\left(\frac{2.4r}{r_o}\right)\right]^3$$

The total change of k is

$$\Delta k = \alpha(T_2 - T_1)\iint\left[\cos\frac{\pi x}{2a}\,J_o\left(\frac{2.4r}{r_o}\right)\right]^3 dx\, r\, dr$$

Similarly, if $\bar{T}$ is the equivalent uniform temperature change

$$\Delta k = \alpha \bar{T} \iint \left[\cos \frac{\pi x}{2a} J_0 \left(\frac{2.4r}{r_0}\right)\right]^2 dx\, r\, dr$$

$$\frac{\bar{T}}{T_2 - T_1} = \frac{\alpha' M}{\alpha M} = 0.63 \; *$$

Since the corresponding number for a cube is 0.61, it is concluded that the conversion factor does not change much with pile shape and may be used safely on our irregularly shaped pile. The fifth column in Table II gives the corrected coefficient. The correction factor becomes 0.96 x 0.63 = 0.60 when we take into account the fact that the slug is two feet down stream from the center of the pile. This location was chosen in an attempt to use the hottest slug.

It is more difficult to correct α'_T. The temperature distribution parallel to the rods seems sufficiently symmetric to require no correction. In a radial direction the temperature should be considerably flatter than that of the neutron flux because of the strong cooling by the empty channels at the side. One might approximate the factor as

$$(.63)^{1/3} = 0.86.$$

$$\alpha'_T = -.86\, \alpha_T$$

$$\alpha_T = -.87$$

This is in reasonably good agreement with the directly measured value of -.75.

Other Observations on the Metal Temperature Coefficient

Several other experiments have been performed which throw light on the temperature coefficient in the metal. All of them are complicated by the fact that measurement was made on a slug a considerable distance from the center of the pile and that neither theoretical or experimental methods are entirely satisfactory for determining the position of the active center.

The first of these measurements has been previously reported in CP-1081. The experiment was performed by Mr. Fermi principally for the purpose of determining the power output of the pile. However, while the metal was hot the critical position of the control rod was found, and the temperature coefficient was reported to be approximately -.8 ih/°C for the particular slug. This was corrected to give a coefficient of -.66 for the central slug, which should be -1.05 for the weighted average temperature.

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* We are indebted to Mr. Weinberg for the evaluation of this factor.

This result is considerably higher than those of the previous experiments but is subject to correction on two counts. Such measurements as we have been able to make indicate that the slug is somewhat farther from the active center than was at first thought. There was also a considerable power output in the course of this experiment, enough to raise the graphite of the pile appreciably. Since the temperature difference was measured between the slug and the neighboring graphite, any additional temperature rise in the graphite would give a coefficient apparently too high. For these reasons, the measurement does not seem to be in too poor agreement with the other experiments.

Experiments have recently been performed in which the behavior of temperature and power have been noted after a small shift of the control rod under operating conditions. These measurements were undertaken mainly in an attempt to determine the sensitivity of a control rod in a manner analogous to a long period measurement in a pile at room temperature. However, temperature changes were observed which indicated a temperature coefficient of .7 ih/°C for the particular slug. In this case the corrections for a position in the pile and for mean temperature approximately cancel each other and the final value is unchanged. This is in fair agreement with the previous measurements of α_m. This experiment will be discussed in more detail.

It was also reported in CP-1081 that the temperature coefficient, observed when the pile was being flashed for the W shield experiment, was much lower than any other observation. In this case the power and temperature were rising very rapidly. When this is the case the temperature continues to increase after the pile is in the critical condition. In other words, the lump continues to heat while the power level is going down. In these experiments the temperature indicating devices operated with a long delay time and the effect observed was therefore not the temperature coefficient, but the change in inhours of the pile divided by the maximum possible temperature. This gave us a value of -.4 ih/°C on this particular slug and would be reduced to about -.35 ih/°C for the central slug.

While the observation reported was not very accurate, we may make an interesting calculation from it; namely, the maximum number of excess inhours which the pile can stand without reaching a temperature which would be permanently damaging. This temperature would be approximately 600°C, which is just below the melting point of aluminum and the phase change in uranium metal. If we, therefore, multiply 600°C by .35 we obtain 210 ih = 0.74 % K.

The value of α_m, which we take as -.72 ih/°C, is to be compared with the results of experiments performed in Bloomington (CP-597) on the change of resonance absorption with temperature. This result was very close to one percent change in the absorption per hundred degree temperature rise. To convert this to inhours per degree we multiply by $1 - p$, the probability of resonance capture and convert this figure to inhours. This is

$$\frac{1.0 \times 10^{-2} \times .12}{100 \times 3 \times 10^{-5}} = .4 \text{ ih}/^{\circ}\text{C}.$$

It is possible that the errors in the two measurements may be sufficient to allow agreement. However, the discrepancy appears to be considerable. It would seem advisable to devise experiments to see if any other factor besides the temperature effect of the resonance neutrons may be causing the discrepancy.

An attempt has been made to account for this discrepancy by the temperature distribution in the graphite near the metal. Our thermocouples which measure graphite temperature are located several centimeters from the nearest metal. However, the hottest parts of the graphite are near the line contacts between the slugs and the bottoms of the channels. If these "hot" spots extend into the graphite by a distance of the order of the mean free path and are at approximately the temperature of the metal, the neutrons passing through the spot will be changed in temperature. This would add a part of the effect of graphite in vacuum to the resonance absorption.

However, Messrs. Nordheim and Soodak have calculated the temperature of this "hot" spot and find that the average temperature rise one centimeter from the slugs is only one or two degrees. This effect must, therefore, be negligible.

Temperature Coefficient of the Graphite and Correction for the Atmospheric Effect

The difference $\alpha_T - \alpha_m$ is equal to α_g, the temperature coefficient which would be obtained if the temperature of the metal were held constant and the temperature of the graphite were changed. This is equal to .72 − .72 = .0 ih/°C. Or, within experimental error, the effect of changing the graphite temperature alone is negligible. However, if the reaction were being carried out in vacuum or in an atmosphere of a gas such as helium which does not absorb neutrons, a sizeable negative temperature coefficient would be found. When the pile is operated in an atmosphere of air an increase in temperature decreases the density of the nitrogen in the pile and in this particular case it appears to compensate the temperature coefficient almost exactly. An equivalent change of pressure will change the density of the air by the same amount as the change of temperature. This, therefore, is approximately 748.6/291 times the barometric coefficient. We do not yet have a thoroughly reliable measurement of this coefficient but we do have measurements that indicate that it is between .26 and .18 ih/mm of mercury. If we accept .21 as a tentative value we get -.52 ih/° as equal to α_g. The same corrections gives us -1.23 for α_t in vacuum.

Since the change of density of the atmosphere affects principally the air in the pores of the graphite there is little analagous correction to be made in the case of α_m. Only one sixth of the air in the pile is in the cooling channels. The temperature of this air will be influenced by the metal temperature, but, considering that the metal has only 44 percent as much surface as the graphite, the correction should be 0.52 x 0.17 x 0.44 = +0.04 ih/C°. This gives a value of α_m in vacuum of -0.76.

Discussion

The very considerable negative temperature coefficient α_g cannot be explained by any known effect. It is presumed to be due to a change of η (the number of neutrons produced per slow neutron absorbed in uranium) with temperature. In other words, an increase of the temperature of the graphite increases the average energy of the neutrons which presumably decreases the probability of fission relative to the other reactions which may occur when a thermal neutron is captured. Experimental work now going on at the Argonne Laboratory may verify this effect.

It is also possible to assume an η effect to account for the discrepancy between α_m and the change of resonance absorption with temperature. This would presumably be due to a decrease of the probability of fission due to an increased thermal energy of the uranium atoms. Another possibility is resonance capture by 25 to form 26. This effect may be present with a probability considerably less than that of fission (CP-1255). The increase of this effect with temperature would cause a loss in addition to that observed at Bloomington. However, it seems unlikely that the effect would be large enough.

Table III

	Inhours based on short period measurements	Inhours based on long period measurements**
$\frac{\delta K}{\delta\, ih}$	3.0×10^{-5}	2.3×10^{-5}
α_P	-0.58	-0.66
α_T	-0.75	-0.81
α_T (vacuum)	-1.23	-1.39
α_m	-0.72	-0.81
α_m (vacuum)	-0.76	-0.86
α_m (vacuum) (Calculated from CP-597)	-0.40	-0.44
α_G	0	0
α_G (vacuum) The temperature coefficient due to the air in the pile.	-0.49*	-0.63
$\frac{\delta\, ih}{\delta\, mm\ Hg}$	0.20*	0.25
	This section of the report uses the figures in this column.	This column is based on sounder calibration and is probably correct.

* Previously published data uses the units in Column 2 except the two marked with asterisks which are based on the calibration in Column 3.

** In Section V it is pointed out that calibrations based on short period measurements at start-up differ by six percent from similar measurements made recently. It is probable that this represents a real change in the calibration curve due to changes in the pile between the two sets of measurements. Since most of the temperature coefficients were measured some time ago the earlier periods give the better calibration. For that reason the figures in this column are raised 14% instead of 20%.

Section IV

The Reactions of the Running Pile to a Movement of a Control Rod

Problem Assignment No. 100X1P

H. W. Newson and R. McCord

We have previously discussed the usefulness of the inhour unit because of its unambiguous definition in terms of directly measureable quantities. However, it is abundantly clear that calibrations must be based on long period measurements if accurate results are to be expected. Unfortunately, in anoperating pile long period measurements are very inconvenient. It is not only necessary that the pile be shut down, but it must also be at such a temperature that changes are not likely to occur during the measurements. This implies a relatively long waiting period while the graphite reaches thermal equilibrium with its surroundings. In the calibrations described in Section V, it was fairly convenient to perform these measurements once to standardize the whole set of calibrations, although the accuracy of the measurements suffered considerably because of an attempt to perform them in the shortest possible time.

It will shortly be necessary to introduce poisons into the pile in order to increase its power output. Reasonably well calibrated control rods will be very useful to check the progress of the poisoning experiments. However, this poisoning will change both the sensitivity and the shape of the calibration curves. It would seem out of the question to shut the pile down frequently enough to recalibrate with long periods on the cold pile. An attempt has, therefore, been made to substitute a measurement on the operating pile.

When a chain reacting pile is off the critical condition it rises or falls according to the equation

$$\frac{d \ln n}{dt} = \frac{1}{\tau} = \delta \text{ ih}$$

if the period is long. Where n is proportional to the power output of the pile and τ is the period.

A pile operating under equilibrium conditions at high power, however, will suffer a change of temperature for a very slight movement of the control rod. This change of temperature will be proportional to a change of inhours = $\alpha(T_o - T_2)$. Where α is the temperature coefficient, T_o is the temperature under critical conditions and T_2 is the temperature at time T after the control rod has been moved. Combining these two equations we find that

$$\frac{d \ln n}{dt} = \delta \, ih - \alpha (T_o - T_2)$$

This equation will not be exact since the equilibrium between the instantaneous neutrons and the delayed neutrons is continually being disturbed by the temperature changes. However, Mr. Nordheim has developed an ingenious empirical correction which may be applied, (M-CP-1295).

Figure 1 shows a plot of the power level of the pile and of the temperature against time. The two curves are similar, but the minima are considerably displaced. It is probable that the pile had not reached thermal equilibrium at the time measurements were stopped, but there did not seem to be any possibility of following them further with much accuracy. New instruments are on order which will probably perform this task and follow the complicated temperature changes which probably take place for at least an hour after the change. The main effects from these curves are probably due mainly to the change of metal temperature and the latter part to changes in the graphite temperature which, however, have probably not reached equilibrium.

Figure 2 shows a plot of $d \ln n/dt$ against $T_o - T_2$. This is plotted only as far as the temperature minimum, which is the interesting region of this plot. This is extrapolated back to T_o, which gives us a period of 1.3 reciprocal hours. This is equal to the number of inhours within 2%. From Jones' control rod calibration we know that the movement of the rod was equivalent to 1.6 inhours. The result of the extrapolation is, therefore, low. The lower curve, shown by crosses within circles, is Nordheim's correction. This extrapolates to exactly 1.6 ih. The method has not been carried far enough, as yet, to determine the accuracy with which standardizations may be made by this method. However, most of the difficulties which have been encountered seem to stem from the instruments which are those built into the control panel of the pile and are not very suitable for the purpose. There seems good reason to suppose that better instruments would allow the pile to be standardized with sufficient accuracy by this method. The temperature coefficient α should, at first be α'_m, the uncorrected coefficient for the metal as explained in Section III.

After the elapse of some time α should be equal to α_p. However, provided α does not change rapidly during the course of the measurements, its value is not important for our present purpose. It will be observed from the corrected curve that the slope corresponds to .14 ih per arbitrary temperature unit or .82 ih/°C. The thermocouple was in a position where its intensity relative to the center was .8. α' at the center should, therefore, be .57 ih/°C. If the inhour change during the experiment is divided by the temperature change from the initial conditions to the final value a coefficient of 1.0 ih/°C is found. If we convert this to the activity center we obtain .8 ih/°C. These values are somewhat difficult to compare with the results reported in Section III. α'_m, as given there, must be converted to the new calibration and corrected for the fact that the slug is somewhat off center. This gives -.43 x .96 x 1.2 = -.49 ih/°C. α_p must also be corrected in order to compare with measurements at the center, since the center of the pile is off the maximum of the temperature curve for which α_p applies, this correction will raise it somewhat. The value should be approximately .66/.95 = .70. The agreement of .57 with .49 is within the spread of measurements of α'_n. The value of .8 exceeds the value α_p by about the same amount. Considering the errors in converting from measurements at one point to those at another, this is reasonably good evidence that the temperature coefficients during the short period of time which determines the extrapolation curve is not much above α_m, but that the temperature coefficient does change considerably during the course of the whole measurement. This may be seen by plotting the rest of the points. Figure 2 includes only those points up to the temperature minimum. The rest of the points while near the curve, show a definite trend away from it.

We are indebted to Mr. Kanne and several others for help in assembling the apparatus and in taking some of the measurements.

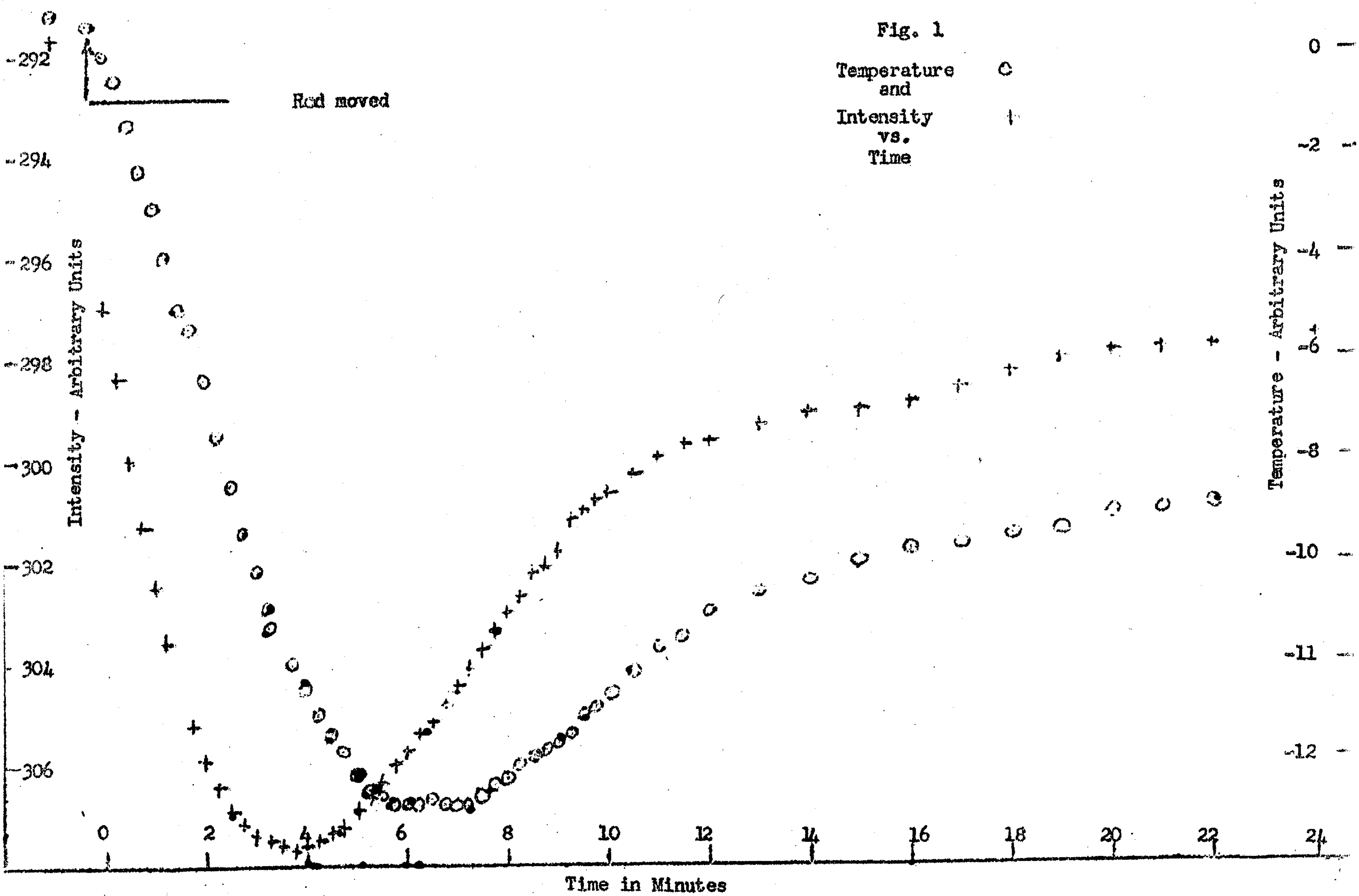


Fig. 1
Temperature
and
Intensity
vs.
Time
Rod moved
Intensity - Arbitrary Units
-292
-294
-296
-298
-300
-302
304
-306
Temperature - Arbitrary Units
0
-2
-4
-6
-8
-10
-11
-12
0
2
4
6
8
10
12
14
16
18
20
22
24
Time in Minutes

Control Rod Calibrations and Absorption Measurements

Problem Assignment No. 100X1P

Haydn Jones

If one attempts to calibrate the control rods of a pile operating at a high power level by making period measurements, it becomes apparent that the method is quite inapplicable due to changes caused by temperature drifts. To circumvent such difficulties, the following procedure was used to calibrate the #2 control rod (0, -10.5 to 18, -7.13):

1. A sensitive type K potentiometer was connected to a thermocouple soldered to the Al can of the 35th metal slug in channel 1859 (0, 0, 9.185). The temperature of this slug was kept essentially constant during a set of measurements by varying the power level of the pile.

2. A cadmium strip 2-1/4" wide x .019" thick was used as a standard unit of reactivity by placing it in slot #58 (-9, -19 to 0, -9) so that it extended 144" into the pile from one edge of the pile to the middle plane (or y = 0 plane) of the pile. This is a region of very low neutron density so that this rather large piece of cadmium had a small effect on the reactivity of the pile (2.8 inhours). The number 2 regulating rod runs parallel to this slot some 73.5 inches away. The perturbation caused by the Cd strip on the neutron distribution was negligible for most of the pile. Any shadowing effect on the #2 rod is well within the experimental errors.

3. Using the #1 regulating rod (0, +10.5 to -18, 6.87) as a compensator, the sensitivity of the #2 rod was determined for various positions of the #2 regulating rod taking the Cd strip as the unit of reactivity. That is, the pile critical position for the control rods was determined for a given position of the #2 regulating rod. Then the Cd strip was inserted slowly and the pile temperature held constant by moving the #2 regulating rod out--i.e., pile was kept operating at essentially the same power level--until the Cd strip was at its "in" position. Then a new critical position was determined. The direction of motion of the cadmium strip and #2 rods were next reversed until the Cd strip was again out of the pile and a critical position again determined. When we first tried such measurements, we held the power level constant during the manipulations, but the slight temperature changes introduced considerable error.

Figure 1 shows the sensitivity curve measured in this way.

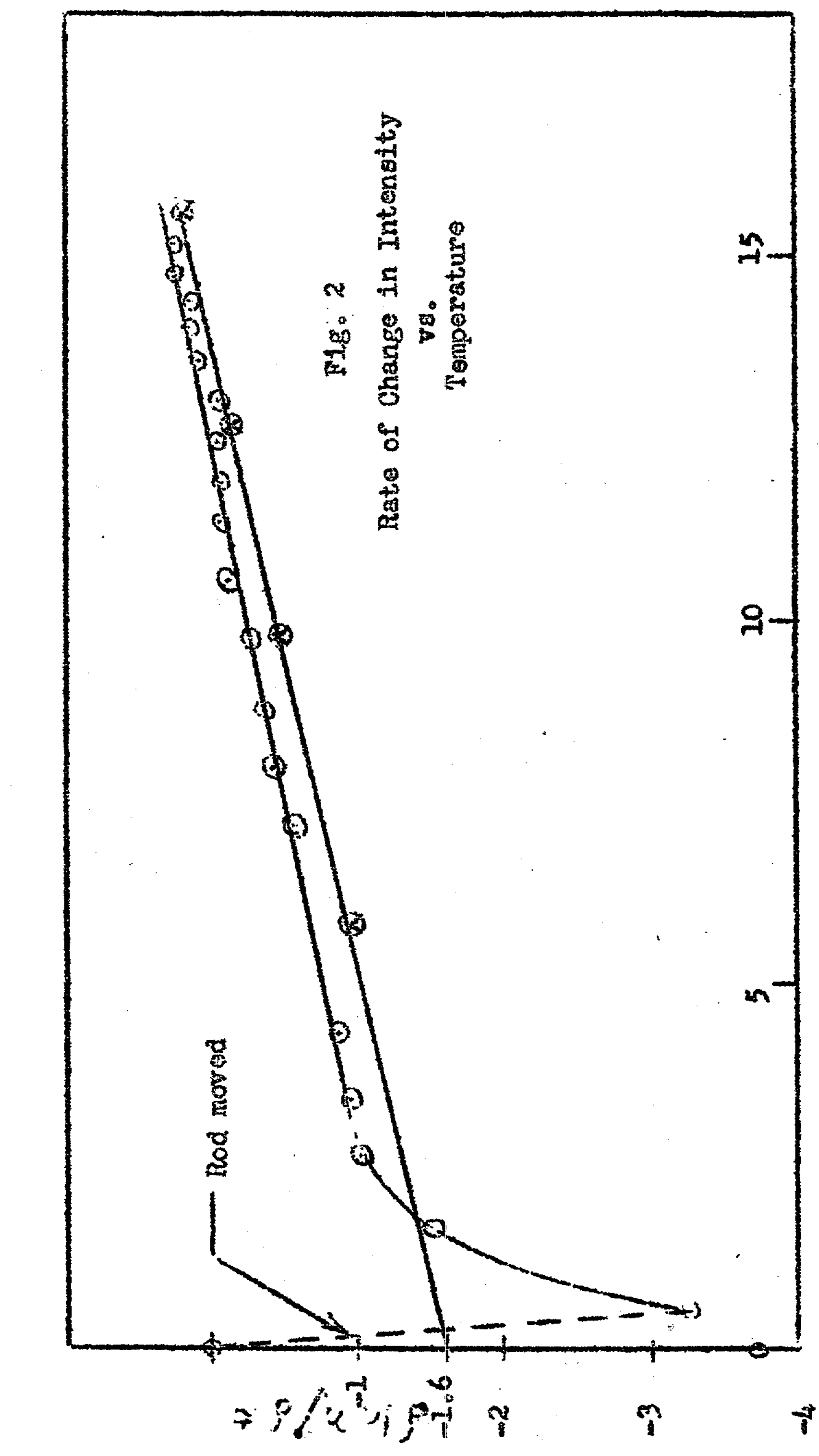
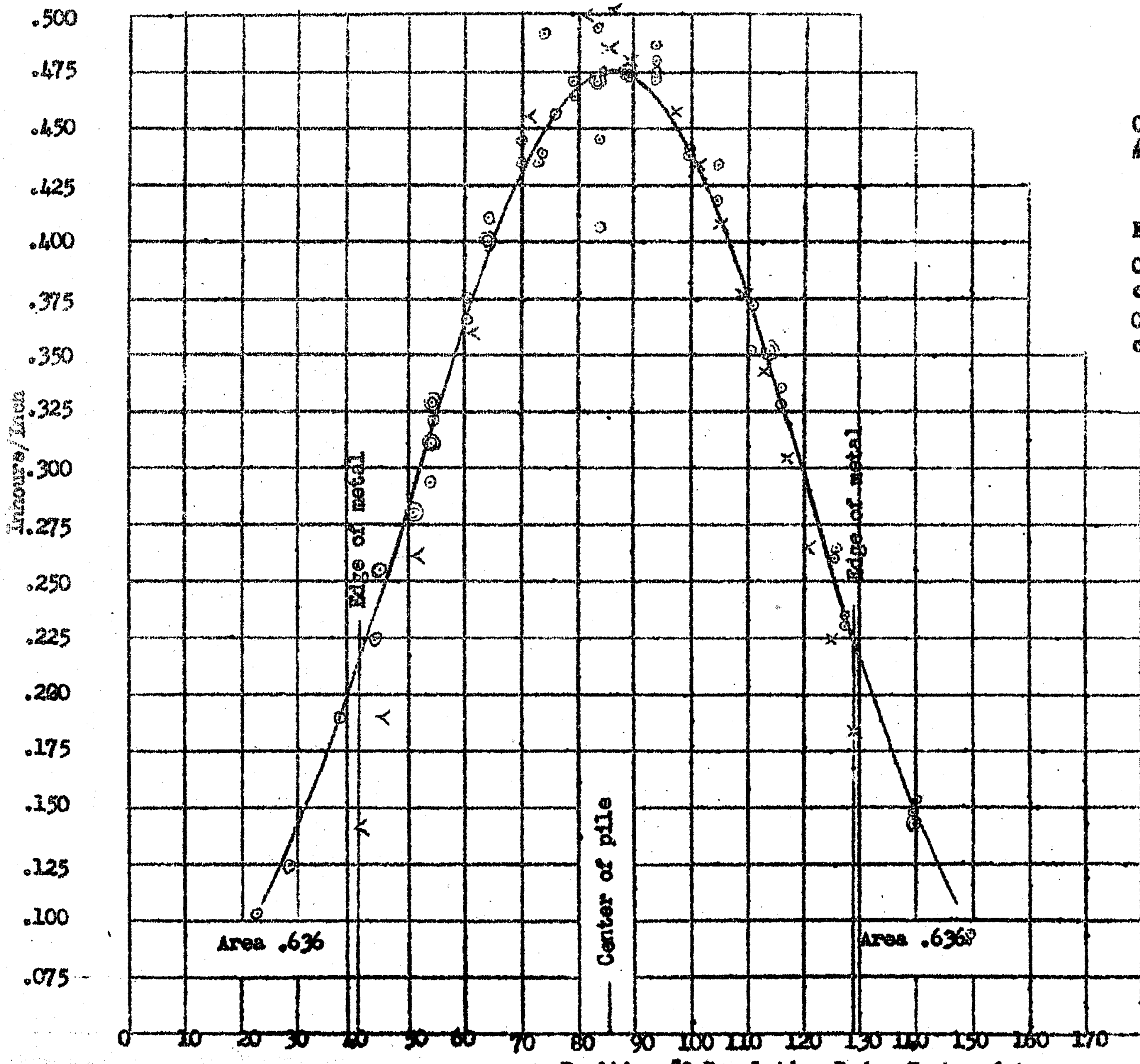


Fig. 2
Rate of Change in Intensity
vs.
Temperature



Calibration of
#2 regulating
rod

Experimental points

Calculated points
center at (0, 0, 2.28)

Calculated points
center at (0, 0, 3.78)

Figure 1

1-14-44
H.J.

The setting of the selsyn is essentially correct since the center of the pile 85.5" was designed to have occurred at a reading of 84" out.

Two attempts were made to fit the experimental data by a Bessel's function. These are shown in Figure 1. Since control rod #2 cuts through only a small portion of the metal lattice, the theoretical fit could not be expected to be perfect. In the case of the #1 control rod, the fit with a Bessel's function was excellent, the average percentage deviation being 4.2%.

4. The absolute reactivity of the Cd strip was determined at a later date from pile period measurements made with the pile cold and operating at very low power levels so as not to disturb the pile temperature.

Four separate methods were used:

(1) The standard Cd strip was in the pile when it was started and brought to essentially a critical position. Then the Cd strip was removed from the pile and the period measured (1280 seconds) to give 2.73 inhours for the strip as calculated from the inhours formula (adopted from the formula used for the Argonne Pile). A correction of 0.22 inhours had to be made to this value to correct for the fact that the pile was slightly off the critical position before the Cd strip was removed. The corrected value equals 2.95 inhours.

(2) The pile was running at a constant power level. A Cd strip was inserted into the pile. The measured period was -1302 seconds which is equivalent to -2.84 inhours.

(3) With the pile at a critical position, the regulating rod was moved out so as to give the pile a period of 2913 seconds which is equivalent to 1.22 inhours reactivity. Then the Cd strip was inserted to give the pile a period of -2615 seconds or a reactivity of -1.39 inhours. The difference in these reactivities should be that for the Cd strip or 2.61 inhours.

(4) With the controls set to give the pile a period of 558 seconds or a reactivity of 6.07 inhours, the insertion of the Cd strip decreased the period to 1057 seconds or a reactivity of 3.29 inhours. The difference in reactivity due to the Cd strip is then 2.78 inhours.

The average poisoning effect is taken as 2.8 inhours for the standard Cd strip. This value which was taken with the pile cold may be very slightly high to use as a hot pile value (1%).

If one integrates the sensitivity curve over its length, one gets the total number of inhours equivalent for the entire #2 control rod. This gives 39 inhours which should be compared with period measurements made for the almost complete removal of the #2 rod which gave an average of 34.74 ± 2 inhours.

The discrepancy is likely due among other things to an error in the constants of the reactivity vs. period formula used.

Calibration of #1 Control Rod

The #1 control rod (0, 10.5 to -18, 6.87) was calibrated by comparing its sensitivity against that of the #2 control rod. Critical positions were taken for about 2" movements of the #1 control rod. Since the #2 rod has a smaller effect on the pile than the #1 rod, it was necessary to insert extra Cd strips into slots 59 and 60 to maintain the same level of operation. These Cd strips undoubtedly perturbed the measurements to some degree. However, the continuity of the data shows that the effect was very small.

A least squares zeroth order Bessel's function fit gave the sensitivity in inhours per inch as

$$2.922\, J_o^2 \left(\frac{2.4048}{115} \sqrt{y^2 + (30.25)^2} \right)$$

where, 30.25" = distance from center of active lattice to control rod channel.

y = distance from y = 0 plane along the control rod channel $|y| \leq 88"$.

115" = effective radius of pile = 292 cm,

2.922 = sensitivity in inhours per inch of such a control rod at the center of the central cell.

Using information about the neutron distribution in the graphite shield, one can write a formula which applies to the graphite region of the control rod's travel as

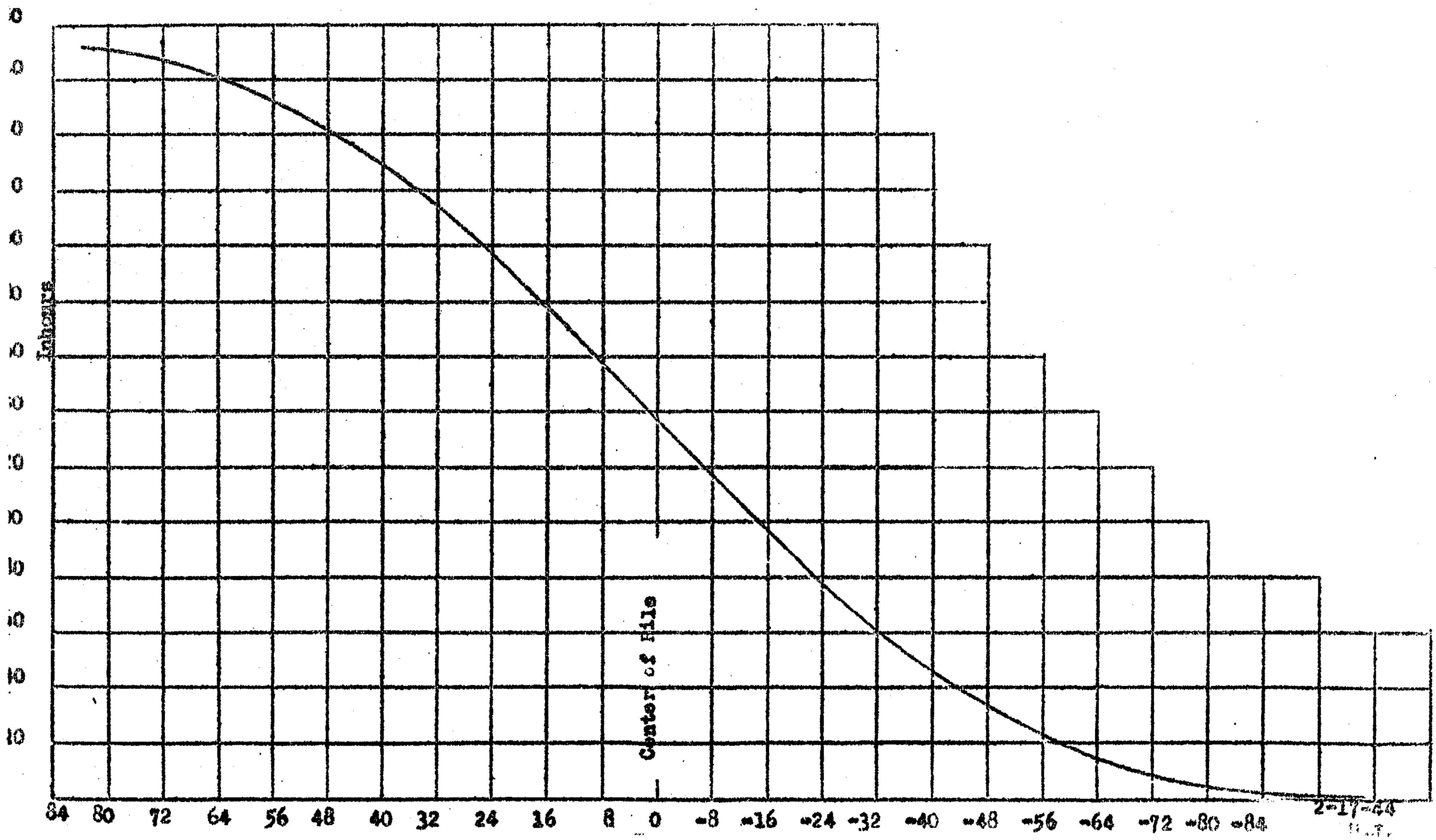
$$4.78 \times 10^{-4} \left[e^{\frac{(148.44 - r)}{18.6}} - e^{-\frac{(148.44 - r)}{18.6}} \right]^2$$

where, 18.6" = the relaxation distance = 47.24 cm
148.44" = radial distance to a point where the effective neutron density is zero
4.78×10^{-4} = normalization constant in inhours per inch
$144" \geq |y| \geq 88"$ $\qquad r = \sqrt{y^2 + (30.25)^2}$

An integral curve of the #1 control rod is shown in Figure 2. The values in the region of usual pile operation around -25" are about 14% higher than those obtained from the initial pile start-up data and about 20% higher than recent period measurements gave. These differences may be caused in part by the constants used in the inhours vs. period formula.

FIGURE 2

Calibration of #1 Regulating Rod



Ripple Experiment

Having calibrated the number 2 regulating rod, we decided to study the ripple in the slow neutron intensity caused by the rod structure of the lattice. To do this we placed small pieces of Cd sheet on an aluminum strip so that they could be moved back and forth in a foil slot across the central vertical plane ($y = 0$ plane) of the lattice.

1. Three 2" x 2" x .020" Cd pieces were scotch taped 8" apart (the lattice spacing) to an aluminum strip. The strip was slid to the center of the pile, i.e. the center of the middle Cd piece was in the $y = 0$ plane. Measurements of critical positions were taken at two inch intervals over the central 32 inches of the lattice. Runs were made in slot #50 (9, -2 to 2, 9) and slot #52 (-9, -2 to 2, 9) where the graphite temperatures were around 20°C and 75°C. No observable difference due to temperature flattening was measurable. Figure 3, shows the experimental results.

When a correction is made for the general shape of the pile intensity distribution in this region you get Figure 4. The general downward drift is caused by the fact that different amounts of aluminum are in the pile for the various measurements.

The similar measurements made with five 1" x 2" x .020" Cd pieces spaced 8" apart are also included.

The ripple had been measured earlier using Cu foils as detectors. A 5% variation in intensity was observed. The transition region between the graphite shield and metal-loaded lattice has been investigated using 10^{-6} gram indium detectors. (Technique described elsewhere in this report.) Typical results shown in Figure 5 indicate a 7% ripple. The control rods have a vanishing small ripple due to the fact that the rods absorb all of the neutrons in their neighborhood so that there is nothing left to ripple.

Axial Distribution

A 2" x 6" x .020" Cd piece scotch-taped to an aluminum strip was run into slot #62 (18 to -18, 0, 0). This foil slot runs parallel to the metal rods. Critical position measurements were taken for one foot movements of this Cd piece. In order to eliminate long time drifts of the pile and to help locate the center and ends of the intensity distribution more accurately these data were analyzed to give us essentially the derivative of the square of the neutron intensity. The curve of Figure 6 is the sin 2θ with a width of 300" and its midpoint (.51, 0, 0) at 12.34 feet from the front face (18, 0, 0) of the graphite. The metal rods 1.1" diam. run parallel to the x-axis starting 21.5" from the front of the graphite and extending to the rear edge of the graphite being composed of 65 aluminum-coated metal slugs 4.1" long. That is for the main central cylinder of the pile, the metal extends from $x = 15.2$ units to -18.

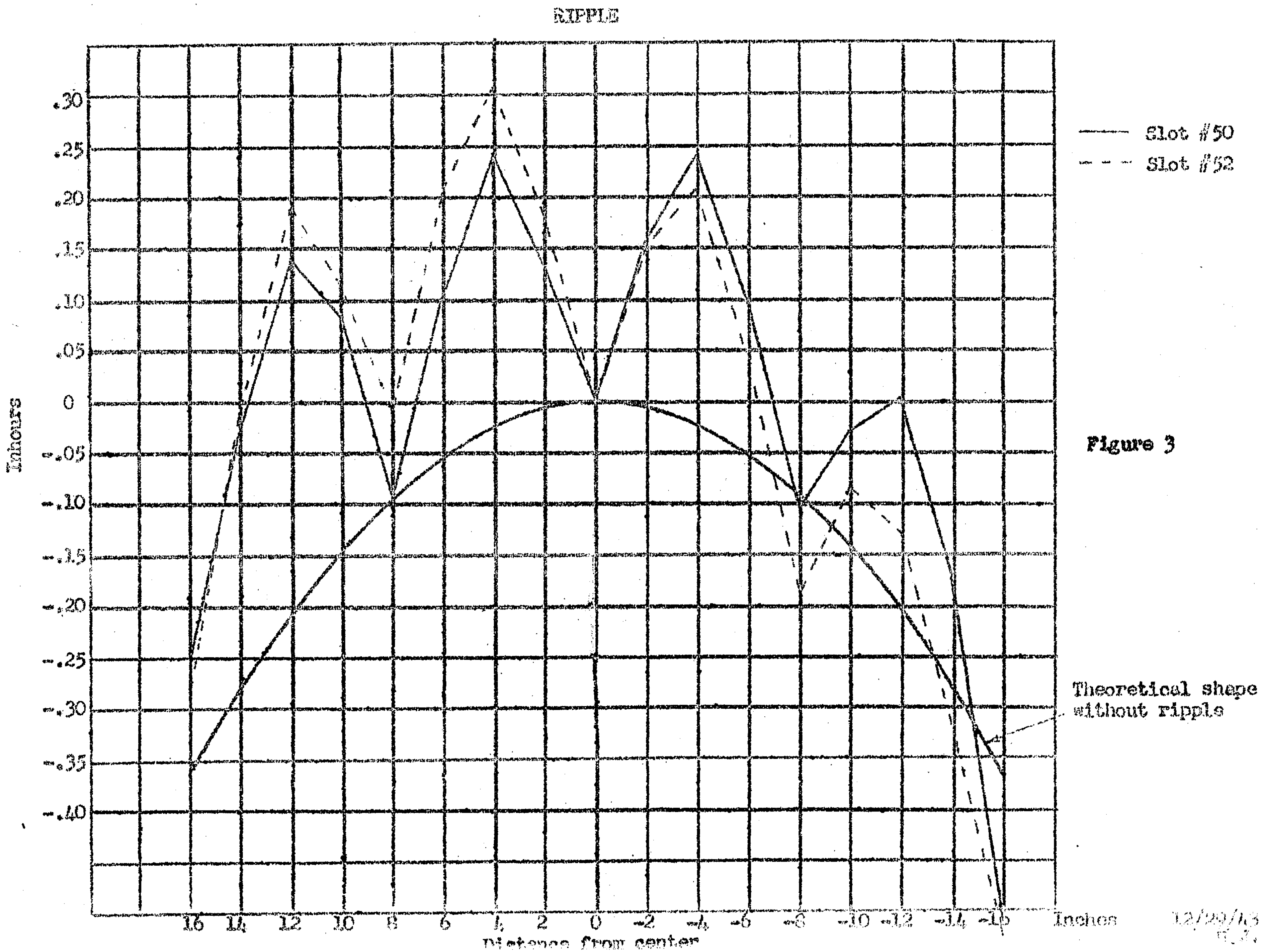
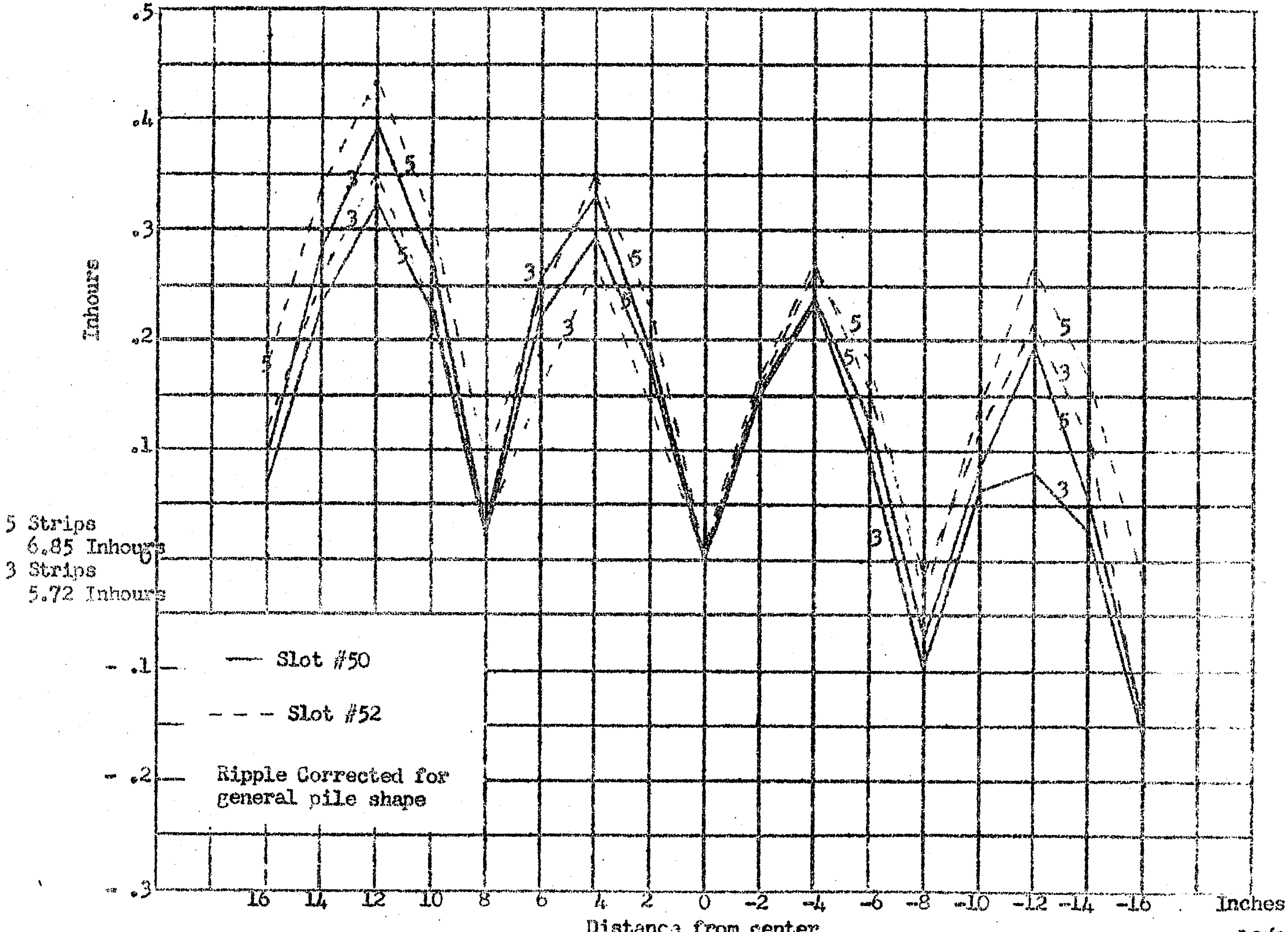


Figure 3

12/29/43



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H.J.

Figure 4

FIGURE 5

Ripple Corrected for General Pile Shape

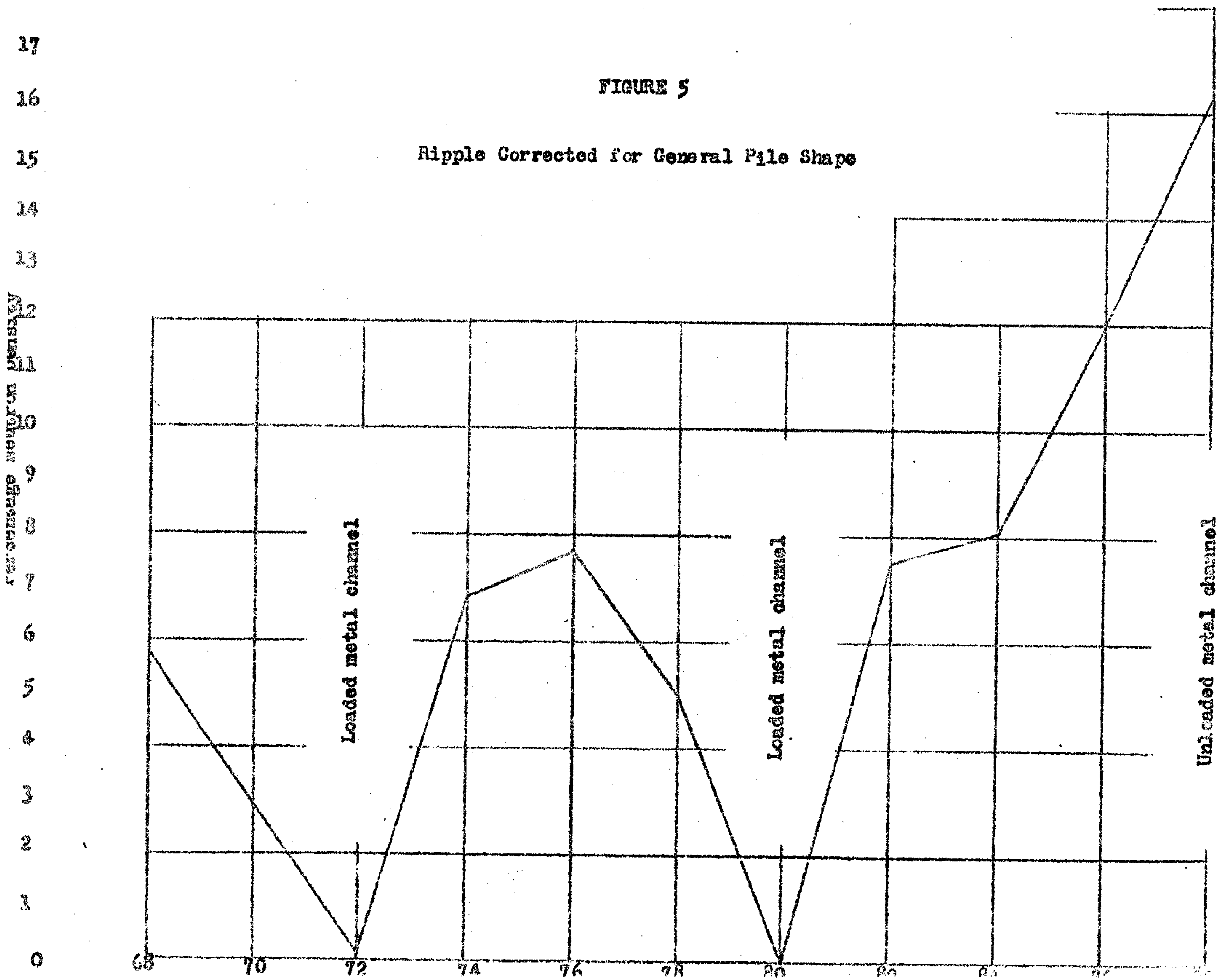
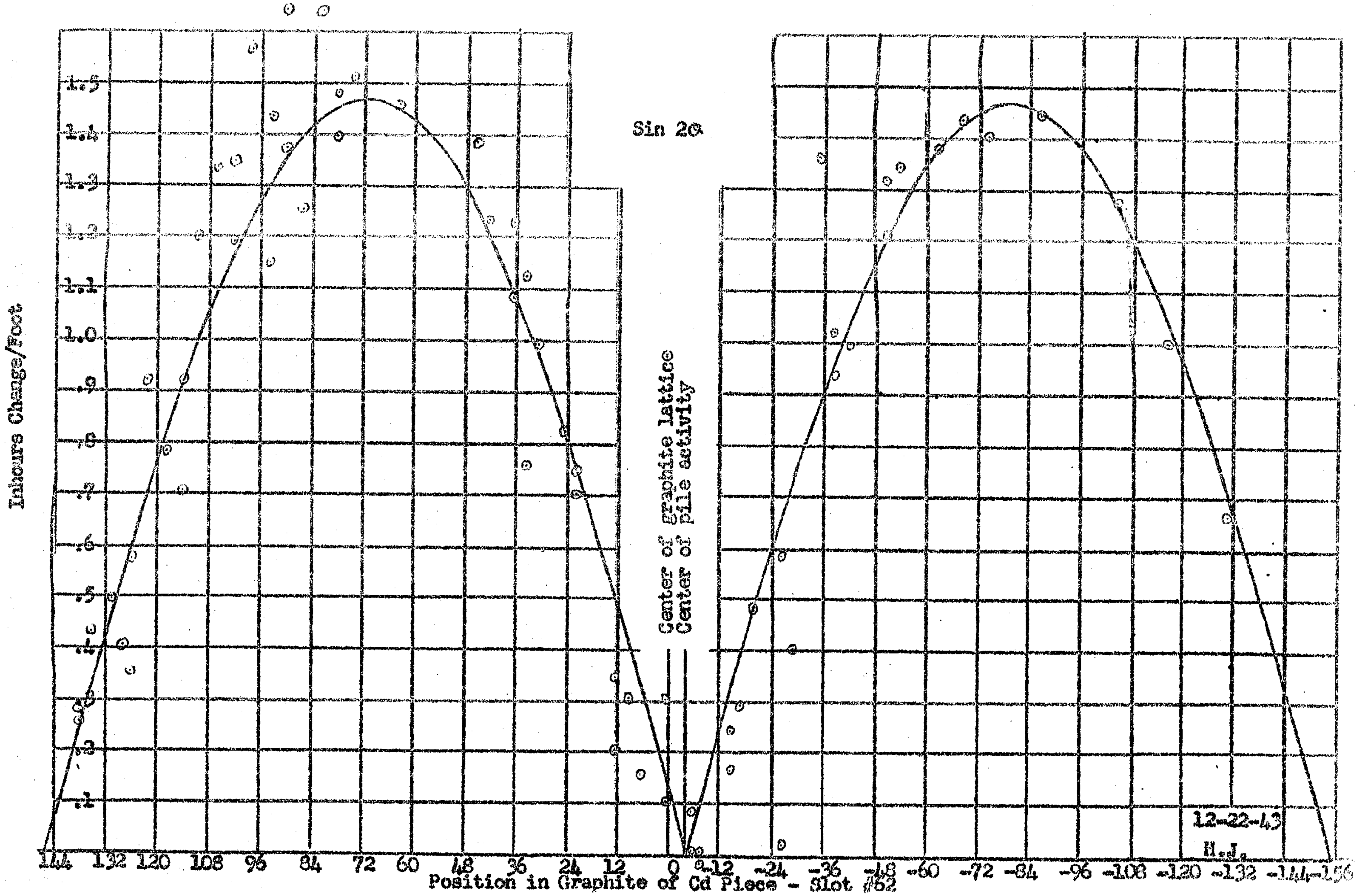


Figure 6


Sin 2θ
Inhours Change/Foot
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
Center of graphite lattice
Center of pile activity
144 132 120 108 96 84 72 60 48 36 24 12 0 0 -12 -24 -36 -48 -60 -72 -84 -96 -108 -120 -132 -144 -156
Position in Graphite of Cd Piece - Slot #62
12-22-43
H. J.

The experimental points, Figure 6, show that the intensity of neutrons along the axis-cylinder quite accurately fit a cosine curve of width $\pi \approx$ 300" ± 1" and zero angle at 4.08" back of the center of the graphite lattice.

Effect of Poisoning

A Cd wire 0.1016 cm diameter and 140 cm long was scotch-taped to an aluminum strip and inserted in slot #62 (18 to -18, 0, 0). Critical positions were taken for one foot axial shifts of the wire. Assuming that the pile intensity follows a cosine function along the cylinder-axis, we calculate the curve drawn in Figure 7, where the abscissae are distances from the center of the pile intensity to the center of the 140 cm length of Cd wire. When adjusted by the method of least squares to the experiment points we get the sensitivity

$$\frac{dR}{dx} = \frac{9.42}{L} \int_a^b \cos^2 \theta d\theta$$

where R is in inhours and L is the length of the wire in feet between a and b. Using this formula one calculates that an eight inch (width of cell) piece of Cd (diameter = .1016 cm) placed in center of slot #62 would effect the pile by 0.82 inhours or for the central cell of the pile it would effect the pile reactivity by R = 1.0096 inhours.

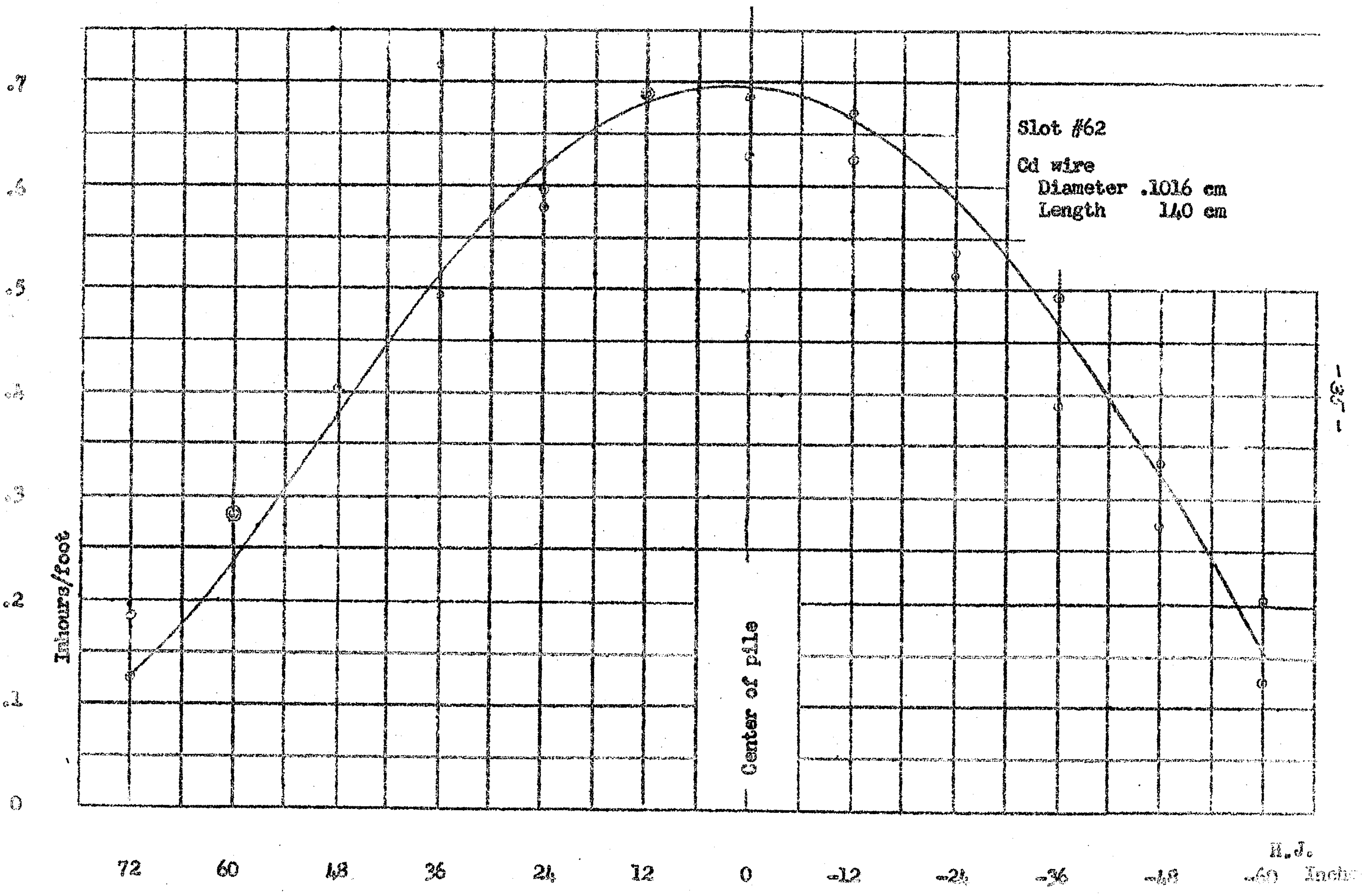
Using $\Delta k = \frac{k}{\sigma cell} \frac{\sigma cd}{\sigma cd}$, where Δk is the change in k near k = 1; $\sigma cd = \frac{\pi}{4}$ diameter x length of Cd wire, i.e. effective cross-section of Cd wire in the cell; $\sigma cell = \frac{1}{1.4} \frac{Vu \, \rho u \, \sigma u}{Au} N + \frac{Vc \, \rho c \, \sigma c}{Ac} N$

with V = volume of material in cell, ρ = density, σ = atomic cross-section, N = avogodro's number, A = atomic weight, we get Δk = .0427.

Taking $\frac{\Delta k}{n} = 2.29 \times 10^{-5} R$, where n = the number of equivalent central cells we get $n = \frac{\Delta k}{2.29 \times 10^{-5} R} = \frac{.0427}{2.29 \times 10^{-5} \times 1.0096} = 1847$ central cells.

A second over-all measurement, made at a later date, gave n = 2092 equivalent cells. Feld at the time of start-up calculated that the pile had 5330 equivalent central metal slugs. Since the slugs average 4.1" in length, we have 8"/4.1" = 1.95 slugs per cell. Since the poisoning is proportional to the square, we evaluate: $\frac{\int J^2(x)dx \cdot \int \cos^2 \alpha d\alpha}{\int J(x)dx \cdot \int \cos \alpha d\alpha} = 0.608$,

Figure 7


Slot #62
Cd wire
Diameter .1016 cm
Length 140 cm
Center of pile
Inhours/foot
.7
.6
.5
.4
.3
.2
.1
0
72
60
48
36
24
12
0
-12
-24
-36
-48
-60
Inches
H.J.

which gives $n = \frac{2.75}{2.29} \times 5330 \times 1.95 \times .608 = 1996$, as the number of equivalent cells on this estimate, where the factor $2.75 \times 10^{-5}/2.29 \times 10^{-5}$ is introduced to correct Feld's value to the constant we used in our calculations.

Using very similar arguments, we calculate the number of equivalent central rods as 102.

Pile Scanning

As we saw in the section on "Axial Distribution", the square of the relative neutron density in the pile can be found by inserting poisoning material (such as a continuous Cd strip) and observing the change of the critical position on a calibrated control rod. This has been done in several foil slots. Typical data are shown in Figure 8, along with a Bessel's function fit and normalized foil scanning data. (See section VI, Figure 4 also.)

In the region of the graphite shield the neutron distribution should fit an expression

$$I = Io\left[e^{\frac{h-r}{b}} - e^{-\frac{(h-r)}{b}}\right]$$

where, r = radial distance from center of pile = $\sqrt{y^2 + d^2}$, y = distance along foil slot, d = distance from most active rod to foil slot, h = radial distance from center where the intensity I = 0, b = relaxation distance. Now, if intensity measurements are taken at equal r intervals and we use sets of three measurements I_1, I_2, I_3 at r_1, r_2, r_3 with $r_2 - r_1 = D = r_3 - r_2$, then the following convenient computation formulas are useful:

$$b = D/\cosh^{-1}\left(\frac{1}{I_2}\right)\left(\frac{I_1 + I_3}{2}\right)$$

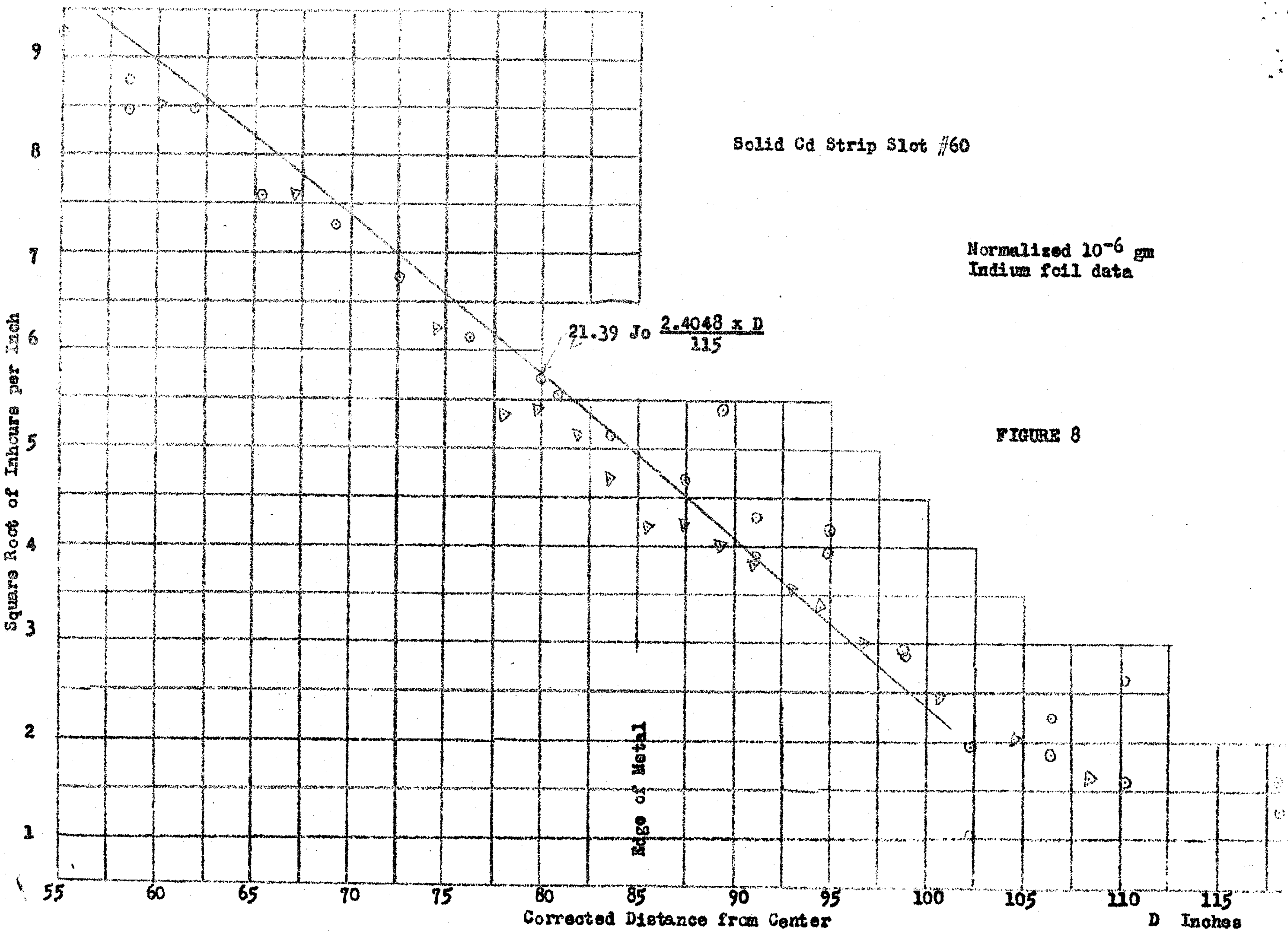
$$h = \frac{b}{2}\ln\frac{I_1 e^{r_2/b} - I_2 e^{r_1/b}}{I_1 e^{-r_2/b} - I_2 e^{-r_1/b}} = \frac{b}{2}\ln\frac{I_2 e^{r_3/b} - I_3 e^{r_2/b}}{I_2 e^{-r_3/b} - I_3 e^{-r_2/b}}$$

Using the small 10^{-6} gm indium foils we have found:

$$I = 441\left[e^{\frac{149.6 - r}{18.6}} - e^{-\frac{149.6 - r}{18.6}}\right]$$

fits the data for slot #59 extremely well with d = 30.25".

I am particularly indebted to G. V. Packer for assistance with the early measurements. R. V. McCord helped with the later work and computations. The foil scanning data taken concurrently by C. Clifford's group often served as a check or a guide to this study. At many points Thelma Arnette and Linda Watson helped with computations. This problem and its method of solution were given to me by H. W. Newson whose encouragement and suggestions throughout its performance were very stimulating.



Solid Cd Strip Slot #60
Normalized 10^{-6} gm
Indium foil data
21.39 Jo $\frac{2.4048 \times D}{115}$
Edge of Metal
Square Root of Inhours per Inch
Corrected Distance from Center
D Inches

FIGURE 8

VI. Neutron Flux Measurements

Problem Assignment No. 100X1P

C. Clifford, T. Arnette, G. Hewitt, L. Watson

Our first measurements of the distribution of neutron flux in the pile were based on measurements of rather large copper foils. A set of these measurements was reported in CP-1081. The copper foils were unsatisfactory at high power operation. The activity was great enough to approach a health hazard, and instruments were not available which would measure the strong activity accurately. A Lauritsen electroscope was actually used. It was found that the reproduceability was poor, and that the decay curves were not consistent. However, one run was made where the copper foils were distributed in all ten foil slots at a spacing of one lattice unit. In all cases the foils were about 3 cm immediately under the metal rods. This set was exposed at low power, and measured on a β-ray counter. The results here were better and a number of interesting effects were observed. However, oportunities for operation at low power are too infrequent to make this a sátisfactory method of procedure, and it was decided to develop foils which could be used at full power operation.

In order to measure the neutron flux in the Clinton pile using counter technique it was first necessary to develop a type of foil which could be counted by the standard thin walled glass Geiger tube, from a metal with known resonance levels and half life and with a reasonable length of exposure time in the intense flux of 3×10^{11} n/cm^2/sec which prevails at the center of the pile at present operating levels.

Since indium is well known and in frequent use it was decided upon. Calculation using the cross section of indium and the approximate nv of the pile at about 800 kw indicated that we would have to use of the order of 10^{-6} grams of metal to get an initial counting rate of six thousand counts per minute after five to six minutes exposure in the pile. It was then necessary to determine some means of constructing a number of standard foils which would have fixed geometry and which could be handled conveniently. To do this we decided to evaporate a fixed quantity of dilute indium nitrate solution upon a small square of cellulose acetate plastic sheet .002 inches thick. We used a technique developed by the micro-chemists involving a .005 cc pipette and a small syringe to deposit a droplet of solution (.2 grams of indium and two cc of concentrated nitric acid per liter). In order to make a reasonable number of foils conveniently we deposited five to ten drops of solution upon a square of cellulose acetate which had been heated in a n aluminum tray at about 70°C to cause it to lie flat in the tray. The drops were then evaporated on the hot plate still at 70°C. After they were evaporated the first sheet was covered by a second of the same size and thickness and both were heated to about 350°C in order to seal them together and prevent the loss of any of the indium. It was very necessary to keep all the operations completely clean as a small amount of contamination was deadly to the results.

The drops were then cut out of the large sheet so that they were in the middle of a foil 1/4 sq cm in area. The foils were kept in cardboard holders to keep them clean and numbered. We tested each foil by placing ten foils in one cardboard holder and irradiating them in the pile. The foils seemed to be quite satisfactory and in the graphite shield of the pile but as we attempted to measure on into the center of the pile we found that we would have to dilute the strength by one third in order to count the foils within an hour after they had been exposed. Since the power at which the pile was running varied we tried the foils at radically different power levels and found a consistent linearity with the galvanometer used to monitor the pile. To convert the data into a useful form we calculated the saturated activity per kilowatt.

In order to protect the personnel the small foils were irradiated in the pile by placing them upon a lucite strip an inch wide and 1/8 inch thick. We checked the strip for absorption by running the foils on a graphite strip of the same dimensions and also upon an aluminum strip and found no variation detectable. The foils were placed in a colored cardboard holder which seemed to become fairly radioactive and which cut the intensity about 4%.

The foils were first made with 1 sq cm of cellulose acetate. However, it was found that bombarding the cellulose acetate alone in the reflector gave a background activity with a half life of about nine minutes amounting to about 1% of the activity of the indium. However, this background increased markedly when bombardments were made near the metal rods inside the active lattice. This indicates that the reaction is due to fast neutrons. It was found that by decreasing the area of the foil 1/4 cm^2 that the background was not serious. However, when a foil is covered with cadmium and the indium count reduced by a factor of 2, the background causes some difficulty. Consequently, the measurements of cadmium covered foils are slightly less satisfactory than the bare foils.

Table 1 shows the results of three runs made with the foils. The reproducibility is, on the whole, good; although somewhat less satisfactory than results of counting standard indium foils. The foils must be handled very carefully in order to avoid contaminating them and for this reason the decay is followed for about one half life and any foil which does not decay normally is immediately thrown out and presumed to be contaminated. Table 2 gives the average count in saturated activity per watt of power output of the pile for various foils both bare and cadmium covered. The cadmium ratio has a nearly constant value of about 1.05 within the active lattice when measured at the boundary of a lattice unit.

Table I

These measurements were made in hole 59 which is nine lattice units upstream from the center of the cooling channels and 3.8 lattice units below the most active rod in the pile. The cadmium covered foils are corrected for a 7% absorption of the resonance neutrons in cadmium.

Distance from slot center	Distance from pile center	As/kw Total	A_g/kw Cd Covered	Total -Cd Covered	Cd ratio
366		5.33			
355		13.2			
345		23.5			
335		32.1			
325		43.3			
315		56.3			
305		71.9			
295		91.0			
285		113.0			
274		141.0	5.33	138	
264		175.	9.63	165	
254		217	14.12	203	
244		265	38.3	227	
239		292			
234		321	64.2	262	
229		351	99.5		
224		383	99.5	282	
218		409			
213	227	428	162.6	267	
208		453			
203		449	208.7	245	
198		502			
193	208	549	268.6	278	1.08
188		576			
183		573			
173	189	664	337	327	.97
152	171	813	394.0	419	1.06
132	153	907	445.0	462	1.06
112	136	1050	486.0	564	1.16
91.4	119.4	1082	640.0	442	.69
71.1	105.0	1151	647.0	504	
50.8	92.1				

Table II

This table shows three typical runs along Slot #59. All runs were without Cadmium.

Distance from slot center lattice units	Run #1 A_s/kw	Run #2 A_s/kw	Run #3 A_s/kw
11	383	382	382
10.75	418	392	408
10.5	429	422	430
10.25	460	438	455
10.00	452	435	454
9.75	498	395	513
9.50	532	535	547
9.25	566	572	582
9.0	572	572	575
10.5	418	403	415
9.5	537	426	528
8.5	623	645	682
7.5	790	806	816
6.5	912	876	898
5.5	1017	1008	996
4.5	1040	1080	1069
3.5	1152	1146	1180
2.5	1196	1265	1202

Figure 1 shows a plot of the intensity of the bare foils. In general, the measurements are made at the edge of the lattice unit, that is midway between the uranium rods. However, for the last cell the active lattice measurements have been made every two inches to investigate ripple. The ripple amounts to a 7% increase of the count immediately below a metal rod as compared to that midway between two metal rods. Occasional points taken farther into the active lattice indicate that the ripple is about the same throughout.

Figure 2 shows a plot of the thermal neutron activity and the resonance neutron activity near the edge of the active lattice. It will be noted that the thermal intensity is nearly flat for approximately two lattice units and shows a slight maximum about one lattice unit beyond the active lattice. These two curves are in good qualitative agreement with theoretical curves predicted by Mr. Friedman: particularly the cadmium ratio inside the active lattice seems to be about as expected. However, Friedman predicts a shorter plateau in the thermal neutron curve in place of the maximum which we have found.

Figure 3 shows a plot of the thermal and resonance intensity as a function of the distance from the center of activity of the pile. Since the Bessel function is nearly linear in that region the plot is extrapolated to zero intensity to determine the effective radius of the pile. This gives a value of 292 cm = 14.4 lattice units. The radius of the active lattice should be approximately 11.5 lattice units, which gives an augmentation distance of 2.9 = 60 cm. This measurement seems to be considerably higher than any theoretical prediction. However, there is a large perturbation, which it is difficult to explain completely in the neighborhood of an empty channel which, up to a point 30 cm from the foil slot, is filled with thorium carbonate. This perturbation leaves a very short linear curve to form the basis of the extrapolation.

Figure 4 shows the thermal and resonance activities plotted on semi-log paper. If an end correction is made assuming that the concrete shielding is equivalent to ten additional centimeters of graphite, a relaxation distance of 47 cm is obtained. This is in very good agreement with the diffusion length of the graphite near the outside of the pile.

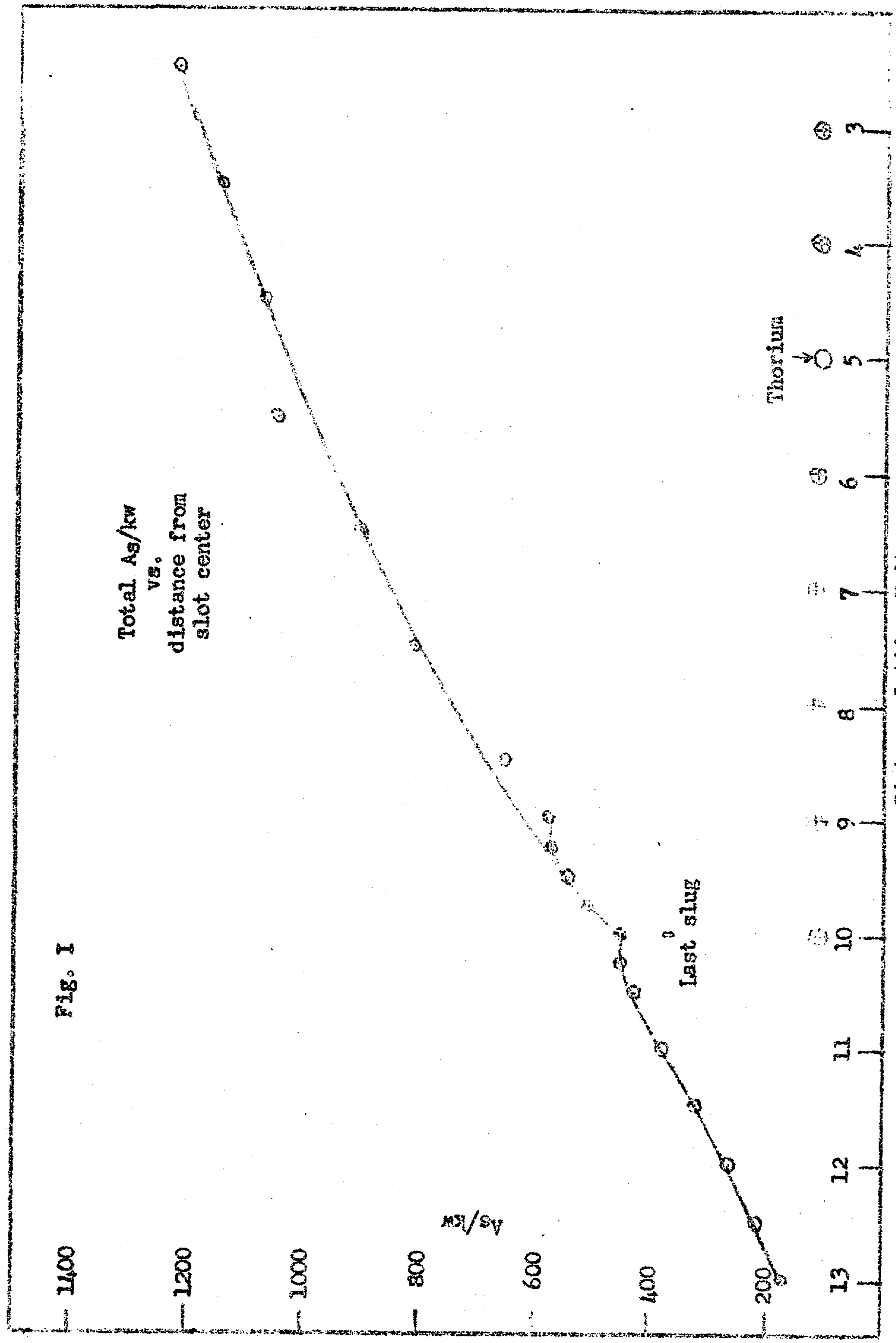
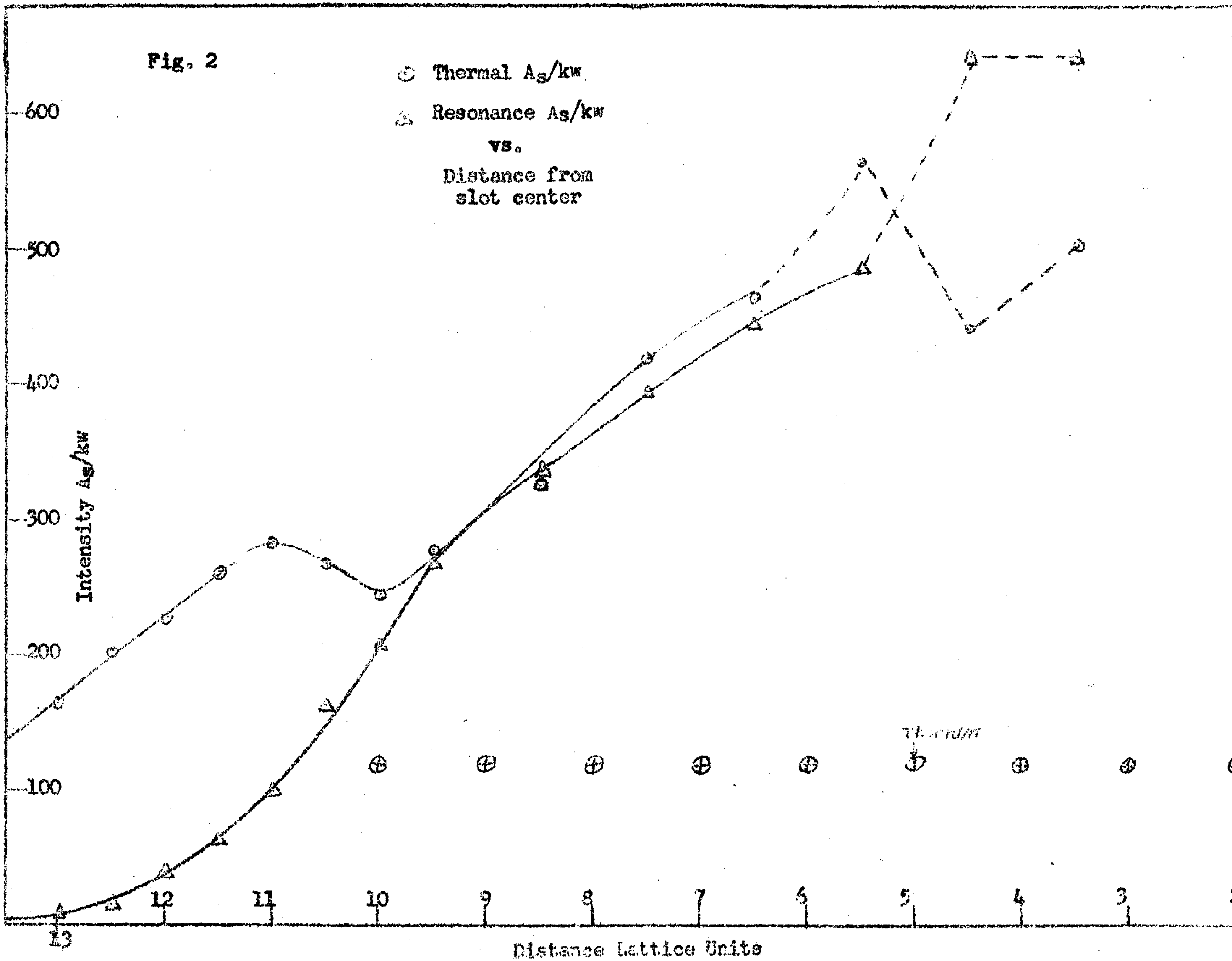

Total As/kw
vs.
distance from
slot center
Thorium
Last slug
As/kw
1400
1200
1000
800
600
400
200
13
12
11
10
9
8
7
6
5
4
3
Distance Lattice Units

Fig. I

Fig. 2


Thermal A_s/kw
Resonance A_s/kw
vs.
Distance from
slot center
600
500
400
300
200
100
Intensity A_s/kw
13
12
11
10
9
8
7
6
5
4
3
2
Distance Lattice Units

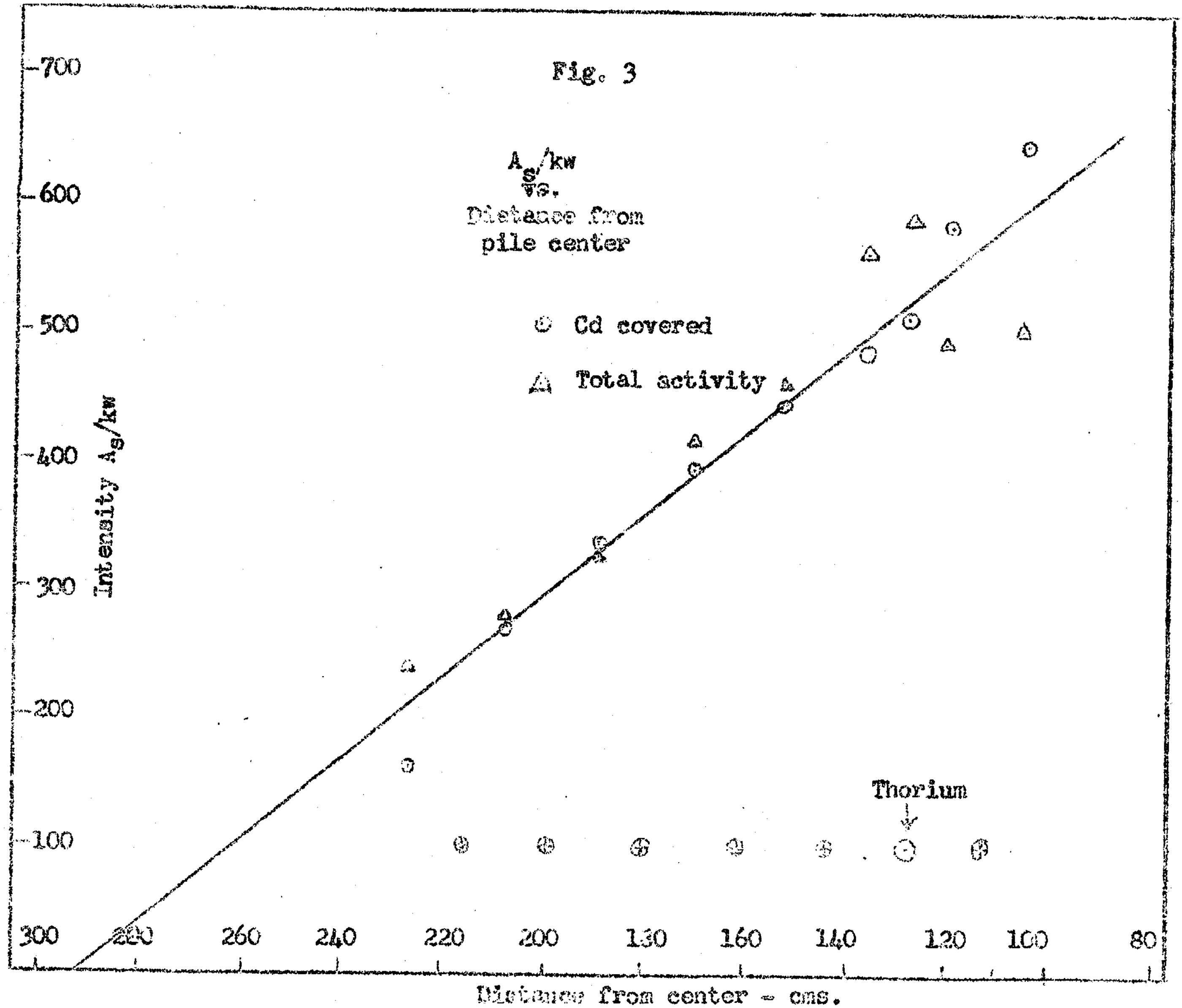


Fig. 3
A_s/kw
vs.
Distance from
pile center
Cd covered
Total activity
Thorium
Intensity A_s/kw
700
600
500
400
300
200
100
300
280
260
240
220
200
180
160
140
120
100
80
Distance from center - cms.

Fig. 4

Thermal and Resonance Activities
in Graphite Shield

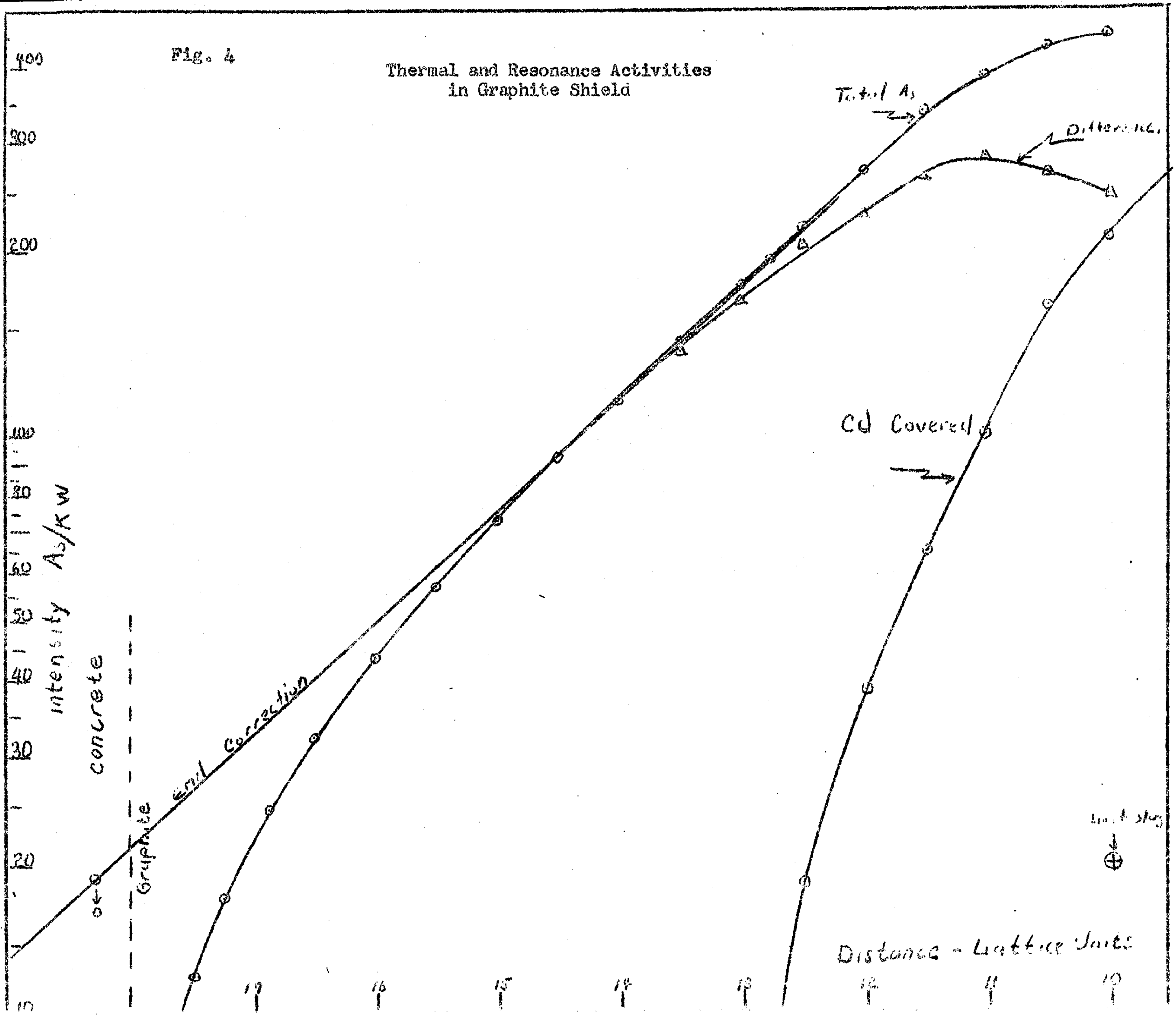
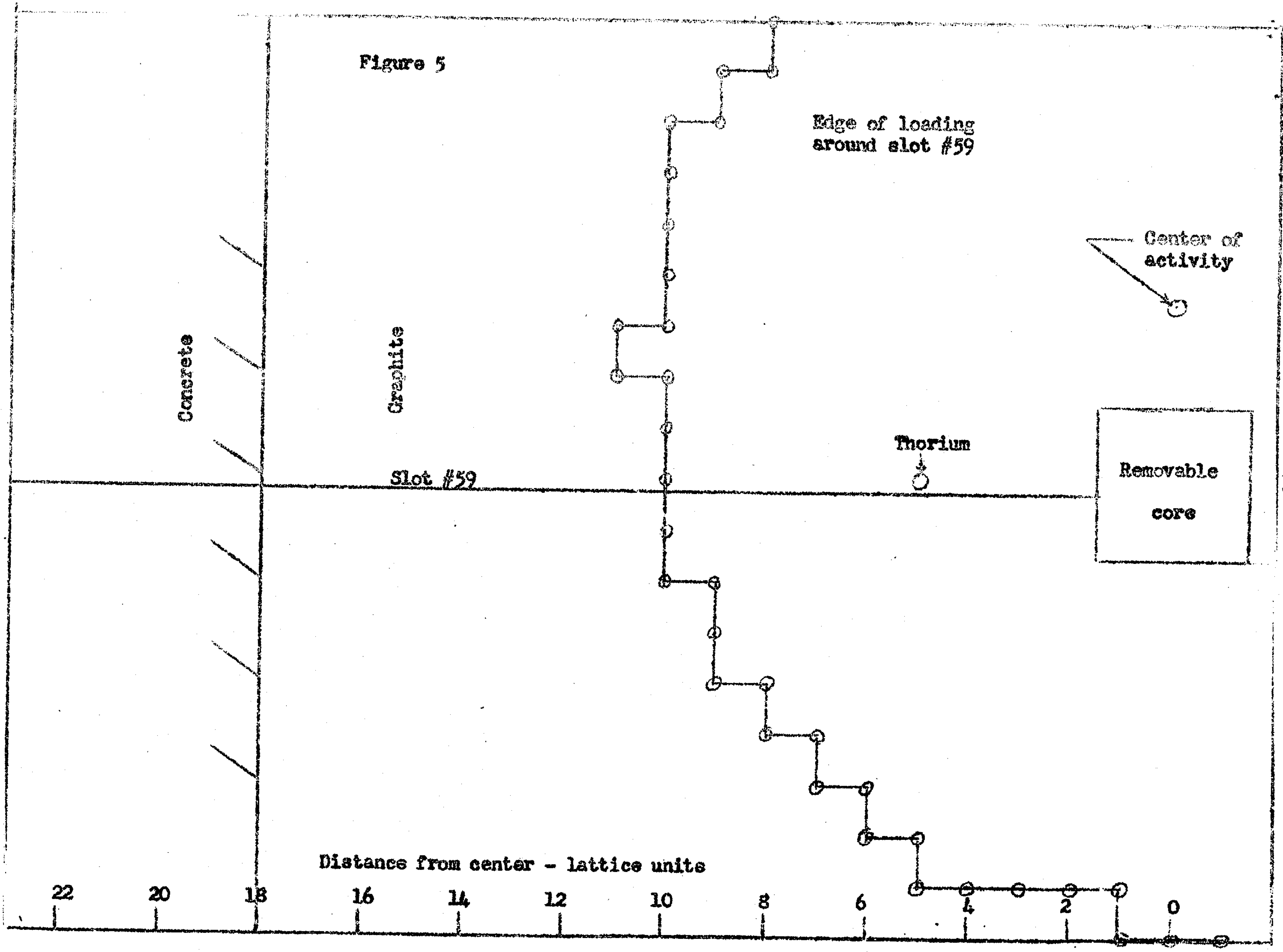


Figure 5



Edge of loading
around slot #59
Center of
activity
Concrete
Graphite
Thorium
Slot #59
Removable
core
Distance from center - lattice units
22
20
18
16
14
12
10
8
6
4
2
0

VII. Radioactivity of Cooling Air

Problem Assignment No. 193X3P

W. R. Kanne and M. H. Wilkening

I. Calibration of the Equipment

Plans for the detection of radioactivity in the pile cooling gas have been described in CT-757, page 5 and Figure 1. Air is sampled from the stack side of the fans, passed through a chamber in which it can be filtered by an electrical precipitator and a glass wool filter if desired, then through an orifice plate, through a large ion chamber and returned to the suction side of the fans. A flow of 15 cfm is provided by the fan differential.

The ion chamber is constructed so as to provide six collecting volumes bounded by planes which serve alternately as high voltage and collecting electrodes. All the electrodes, except the high voltage electrodes which are fastened to the steel shell of the chamber by means of stand-off insulators, are made of an open mesh of wire woven on angle iron frames. This permits beta particles arising in the gas to have the largest possible range. The effective internal dimensions of the chamber are 58-5/16" x 28-5/16" x 28-5/16", giving a volume of 766000 cc.

This chamber was calibrated at Chicago by introducing into it 2560 cc of argon at 76 cm pressure and 32° C which had been activated at the cyclotron by a slow neutron flux of 4.2×10^6 for 45 minutes in a container considered to be 96.7% transparent. This amount of argon was 0.344 of the argon occurring naturally in the air contained in the chamber. The chamber current observed, corrected for the argon decay during and after bombardment was 3.0×10^{-11} amp. The current then to be expected if all the air in the chamber had been bombarded similarly would have been $3 \times 10^{-11}/.344 = 8.7 \times 10^{-11}$ amp. The relation between the nvt to which ordinary air has been subject and the ion chamber current is then

$$\frac{nvt}{amp} = \frac{4.2 \times 10^6 \times 2700 \times .967}{8.7 \times 10^{-11}} = 1.26 \times 10^{20} \text{ n/cm}^2\text{/amp}$$

If the argon cross-section is assumed to be $.62 \times 10^{-24}$ cm^2 one can determine another constant of the chamber, which is .047 curies/cc/amp. This constant has been used to calibrate other ion chambers and Geiger counters in housings by passing the same gas through the calibrated and uncalibrated chambers.

This calibration has been repeated by irradiating argon in the same container in the Clinton Pile. Due to the higher neutron intensity it has not been possible to get as accurate an absolute value for the nv, but a calculation based on the total energy output of the pile during the run and the previous calibration is in good agreement with the nv to be expected at the place in the pile where the argon was irradiated. As a matter of record, this indicates that the container of total length 20" placed into hole #60 to its end at the removable core received an average nv of 2.2×10^{11} per 1000 kw.

II. Analysis of the Argon Activity

No decay periods other than the 110 min argon half life had been observed in the cooling gas before February 16, 1944. However, it was observed early after the beginning of power operation that the air going through the pile picks up activated argon long after the pile is shut down. The curves obtained vary slightly with total air flow, but they all show an abrupt drop in activity followed by an exponential "decay" of about 25 min half life. An extrapolation of these curves to the time of shut down shows that about one-half of the equilibrium activity is due to argon trapped in the graphite and released exponentially with time. A correction for the decay of the argon indicates that it is actually released with a 33 min half life and that one-third of the trapped argon is lost due to decay. The total argon produced is then one-sixth greater than is observed at equilibrium.

It should be remarked that the process giving rise to this observed curve is not understood. According to measurements by Mr. Leverett's group there is about seven times as much air in interstices in the graphite as there is in the air channels. The "instantaneous" drop in activity (actually the drop corresponds to the mixing time in the filtering and ion chambers) is not associated only with the sweeping out of the air in the channels. It seems necessary to assume that some of the air in the graphite diffuses out rapidly and some slowly but we can propose no mechanism which would divide the air diffusing out of the graphite into two components. A calculation shows that all of the air in the pile including that in the graphite contributes to the activated argon observed.

A typical operating relationship is that a chamber current of 1.2×10^{-9} amp is observed when operating at 870 kw (according to the galvanometer) with an air flow of 41,000 cfm entering and 51,000 cfm leaving the pile. The total argon produced would then represent 1.4×10^{-9} amp. and indicate an average nvt $= 1.26 \times 10^{20} \times 1.4 \times 10^{-9} = 1.77 \times 10^{11}$ n/cm² at this wattage. The argon activity under these conditions is 5.65 and 10^{-11} curies per cc.

Even though the average nv per watt in the pile is not well known, a reasonable comparison with the expected nvt may be made. The effective transit time of the air through the pile may be found by dividing the total volume of air in the pile by its rate of flow. The 64 sq in cross section of a lattice unit is composed of about 61 sq in of graphite, 1 sq in of metal and 2 sq in of air. However, only 1/3 are filled, so an average would be 2.7 sq in of air. Graphite contains 22.5% air, so this represents about 61 x .225 = 13.7 sq in of air, giving a total of 16.4 sq in of air per lattice unit, or 16.4/64 = .256 for the fraction of the whole pile that is air. There are then 3,530 cu ft of air in the pile and the average transit time is 3,530/46,000 = .077 min or 4.6 sec. The nv at the center of the pile is 4×10^5 per watt and the average in the pile is one eighth of this, or 5×10^4 per watt. This is an average over both the loaded and unloaded parts. The nvt to be expected for comparison with the observed figure given above is then $5 \times 10^4 \times 870 \times 10^3 \times 4.6 = 2.0 \times 10^{11}$ n/cm^2. Considering the present uncertainty in both the power calibration and the average nv, this is extremely good agreement and the result might be used to calculate one of these if the other were known accurately.

III. Evidence for Fission Products in the Cooling Gas

The stack activity meter has twice indicated activities about 15% in excess of normal with both the precipitron and air filter in operation. The second of these bursts occurred during the morning of February 14, 1944 and several other measurements were made during the period of increased activity. The precipitron caused about 1.1 div/min drift in a Lauritsen electroscope held up to the outside of its chamber and the large air duct in/117 caused a drift of 10 div in 41 sec instead of 10 div in 450 sec, which Mr. Sinclair said had been observed before January 8. A small cylindrical chamber was acting as stack monitor while the large rectangular chamber was running a background experiment. The large chamber showed that the gamma radiation from the precipitron chamber and the pipes almost doubled at this time. Undoubtedly, these two bursts of activity were due to coating failure.

On February 16 further evidence was obtained indicating that large amounts of short lived fission products are entering the cooling air. An increase of about 20% over normal activity was observed in the large chamber and a decay half life of about 4 minutes was observed for this excess activity. It was admitted to the chamber while the precipitron was turned off. Four minutes is approximately equal to the change over time of the gas in the precipitron and large chamber and this measurement is in agreement with the rule of thumb that the half life of fission product is equal to the time since bombardment. It was possible to get much "younger" gas into the small chamber. This was done by permitting about 20 cfm to flow through the large chamber, which is in parallel with the smaller one, and then closing the valve to the larger one. This fills the small one very quickly. More than six times normal argon activity was observed, showing a beginning half life of about thirty seconds. The rapid decay of these materials makes it difficult to state activities at any particular place and time, but it may be estimated that about ½ curie per minute was coming out of the stack at the time these measurements were made. Measurements on February 19 and February 21 showed successive reductions of about ½ in this extra activity, and as of March 1 it seems to be equal to the argon in intensity.

Experiments with the precipitron and the glass wool air filter indicate that the precipitron is highly efficient in removing fission products from the gas stream, but the air filter is only about 50% efficient. The precipitron can be recommended if the removal of such products from a gas is required.

The activity collected by the precipitron can be measured on the outside of its sheet steel housing during operation or very near its plates after opening the housing. It requires about ten minutes to purge the air system and to open the housing. Electroscope measurements were made in both ways periodically both before and after each of the suspected coating failures, yet no activity appreciably above electroscope background was observed except during the second radiation burst. This indicates that the dangers of accumulated contamination are not yet appreciable. On the other hand, there is no record that the chambers were operated with the precipitron off at any time between the two coating failures or after the introduction of the heat exchanger on January 8, and the negative readings on the precipitron can no longer be considered evidence that fission products did not enter the air stream during this time. The records show that the second failure was of longer duration and it may have been the more serious of the two.

The equilibrium background of the large chamber is now (middle of February, 1944) about fifteen times that to be expected on the basis of measurements made in Chicago last August, and about three times that observed late in December, 1943. The total background in the large chamber is now about 5% of the activity due to argon. On February 11 the chamber was purged with non-active air and a decay curve on the background was begun. A single experiment has so far been analyzed into three periods. Strong activities of approximately 34 min and 17 days contribute roughly equal equilibrium intensities and there seems to be an 8 hr period of about 1/20 the intensity of the others. The periods given are not claimed to be accurate. They are probably daughters of fission product gases which either came directly from the pile or were created in the precipitron.

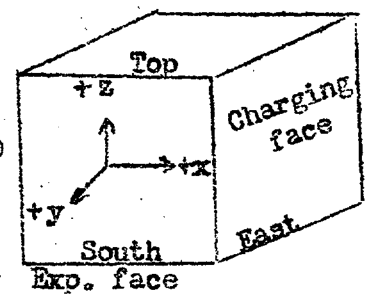
H. W. Newson and L. W. Nordheim have contributed to the work described in this section of the report.

Appendix

The X Pile Coordinate System

It has been found expedient to devise a coordinate system for the X pile to be used in designating positions discussed in reports.

Coordinate x:	east-west direction;	plus, east of x equal 0 minus, west of x equal 0
Coordinate y:	north-south direction;	plus, south of y equal 0 minus, north of y equal 0
Coordinate z:	vertical direction;	plus, above z equal 0 minus, below z equal 0



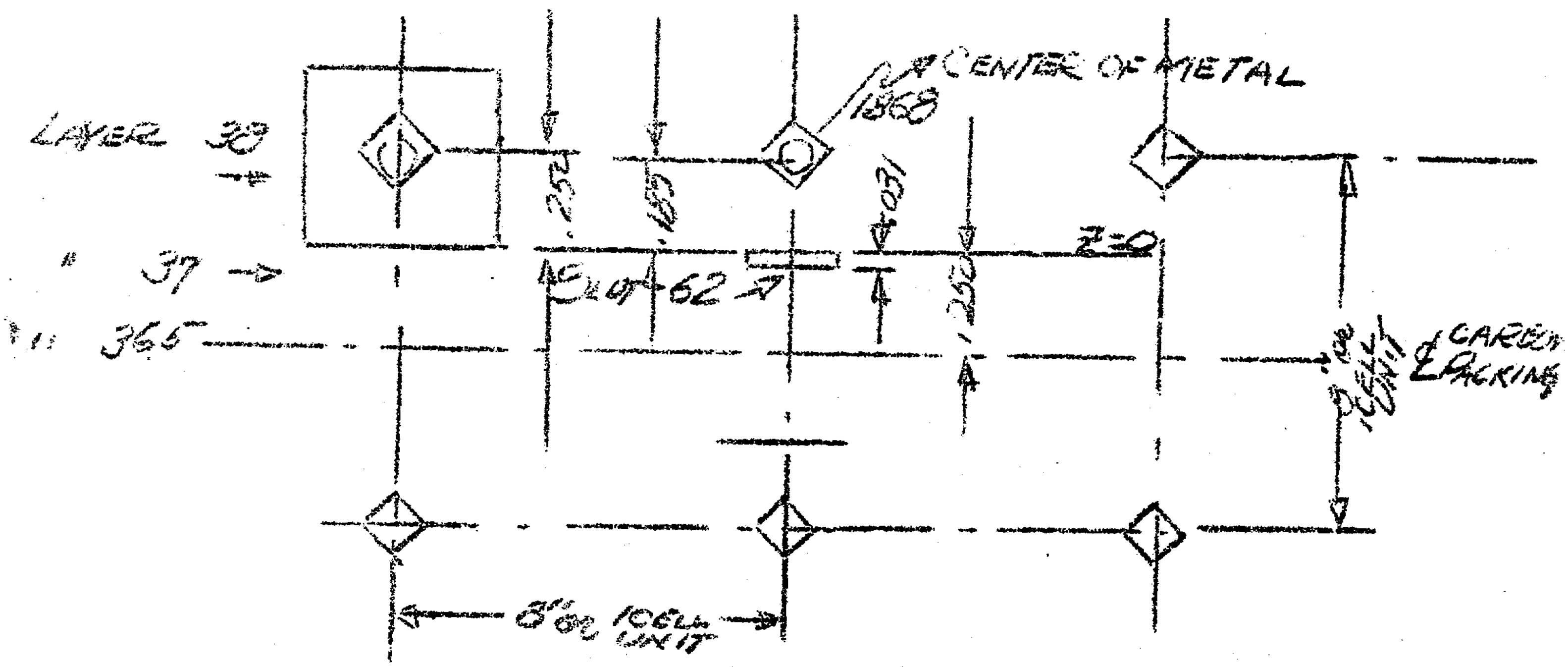
Since a unit cell is 8" x 8" x 8", one unit has been made to equal eight inches. x = 0 and y = 0 are at the geometrical center of the packing and of the metal. z = 0 is in the same horizontal plane as the tops of slots 59, 60, 61 and 62, which is .250 units above the geometric center of the packing.

Sketch No. 1 shows the relationship between z = 0 and the metal channel #1868, which is the geometric center of the metal matrix in the z and y directions.

Given below are the positions, directions, and distances of packing and shield surfaces from the origin.

Position	Distance from Origin
Top of pile (carbon)	z equal 18.00 units - top of layer
Bottom of concrete roof	z equal 19.25 units
Top of shield (outer)	z equal 29.75 units
South outer face	y equal 28.63 units
South inner face	y equal 18.13 units
South packing face	y equal 18.00 units
North outer face	y equal -28.63 units
North inner face	y equal -18.13 units
North packing face	y equal -18.00 units
East outer face	x equal 33. units
East inner face	x equal 22.5 units
East packing face	x equal 18. units
West outer face	x equal -37.5 units
West inner face	x equal -27.0 units
West packing face	x equal -18.0 units

Figure 1



LAYER 38
" 37
" 36.5
CENTER OF METAL
.1868
.252
.189
.031
Z=0
.062
.250
8.60 1CELL UNIT
CARBON PACKING
1 CELL UNIT

Table 1 gives positions and ranges of the rods, foil slots, and experimental holes in terms of the coordinate system.

For example, #56 (9, y, -9) 28.63 to -28.63 indicates that the hole is in the north-south direction and it extends through the packing and shield in both directions to the outer surfaces. It is 9 units east of $x = 0$ and 9 units below $z = 0$.

Table 2 may be used to determine the location of metal regions. For example,

z	x range	y range
1	-18 to 15.3	-10 to 10

describes a horizontal rectangular region of metal extending through the pile from east to west and from 10 units north of the origin to 10 units south of it in the $z = 1$ plane.

It should be mentioned in connection with Table 2's use that it is limited to the arrangement of metal that existed November 15, 1943 since it was based on that loading.

The metal rods of 30 slugs are symmetric with respect to the center of the channel. The rods of 65 slugs are flush against the discharge end and 21.5 inches in from the charging end.

Table 1

Experimental Hole, Foil Slot, and Control Rod Positions

Hole No.	Position	Range of Variable	
1	(0,y,6.75)	28.63 to -28.63	Through shield walls and packing
2	(0,y,-7.25)	" " "	" " " " "
3	(3,y,275)	" " "	" " " " "
4	(-3,y,2.75)	" " "	" " " " "
5	(-3,y,-3.25)	" " "	" " " " "
6	(3,y,-3.25)	" " "	" " " " "
7	(6.25,3.5,z)	29.5 to -6.25	Through Top Past middle of packing
8	(-6.25,3.5,z)	" " "	" " " " " "
9	(6.25,-3.5,z)	" " "	" " " " " "
10	(-6.25,-3.5,z)	" " "	" " " " " "
11	(-.5,-6.5,z)	" " "	" " " " " "
13	(-8,y,1.75)	28.63 to -28.63	Through shield walls and packing
14	(-4,y,1.75)	" " "	" " " " "
15	(0,y,1.75)	" " "	" " " " "
16	(4,y,1.75)	" " "	" " " " "
17	(8,y,1.75)	" " "	" " " " "
18	(-8,y,-2.25)	" " "	" " " " "
19	(-4,y,-2.25)	" " "	" " " " "
20	(0,y,-2.25)	" " "	" " " " "
21	(4,y,-2.25)	" " "	" " " " "
22	(8,y,-2.25)	" " "	" " " " "
30	(12.7-y,18.58)	-28.63 to -12.50	Through shield and on packing
31	(-7.50,-y,18.58)	" " "	" " " " "
32	(7.50,-y,-2.64)	-28.63 to -18.13	Through shield
33	(12.7,-y,-2.64)	" " "	" "
34	(12.7,y,18.58)	28.63 to 12.50	Through shield and on packing
35	(-7.5,y,18.58)	" " "	" " " " "
36	(-12.7,y,-12.95)	28.63 to 18.13	Through shield
37	(12.7,y,-12.95)	" " "	" "
40	(-x,12,11.25)	-37.5 to -27	" "
41	(-x,0,7.25)	" " "	" "
42	(-x,-7,.25)	" " "	" "
43	(-x,7,.25)	" " "	" "
44	(-x,-12,-9.75)	" " "	" "
45	(-x,12,-9.75)	" " "	" "
46	(-20.5,12,z)	29.75 to 19.25	Through top
47	(-21.75,0,z)	" " "	" "
50	(9,y,9)	28.63 to -28.63	Through shield walls and packing
51	(0,y,9)	" " "	" " " " "
52	(-9,y,9)	" " "	" " " " "
53	(9,-y,0)	-28.63 to -1.88	Through north shield wall tocore
54	(0,-y,0)	" " "	" " " " " "
55	(-9,-y,0)	" " "	" " " " " "
56	(9,y,-9)	28.63 to -28.63	Through shield walls and packing
57	(0,y,-9)	" " "	" " " " "
58	(-9,y,-9)	" " "	" " " " "
59	(9,y,0)	28.63 to 1.88	Through south shield wall to core
60	(0,y,0)	" " "	" " " " " "
61	(-9,y,0)	" " "	" " " " " "
62	(x,0,0)	33 to -18	Through east shield and packing
63	(10.5,y,22.70)	28.63 to -7.5	Through south top past center top
64	(14.25,y,22.75)	" " "	" " " " " "

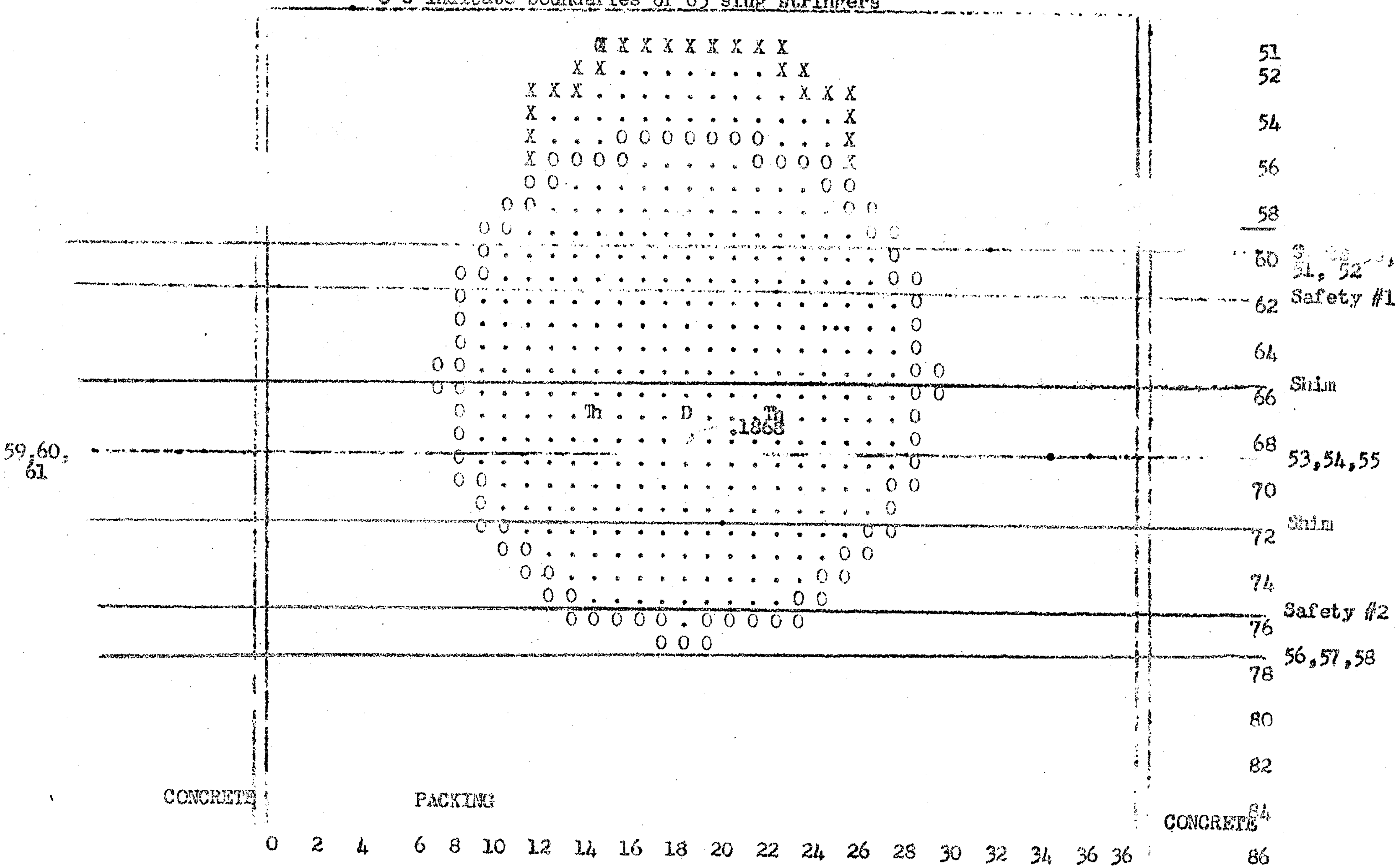
Table 2

Metal Regions in X Pile

z	x range	y range	
0 plus .185	-18 to 15.3	-10 to 10	
1 " "	" " "	" " "	
2 " "	" " "	-11 " 11	
3 " "	" " "	" " "	
4 " "	" " "	-10 " 10	
5 " "	" " "	" " "	
6 " "	" " "	" " "	
7 " "	" " "	" " "	
8 " "	" " "	-9 " 9	
9 " "	" " "	" " "	
10 " "	" " "	-8 " 8	
11 " "	" " "	-7 " 7	
12 " "	-7.5" 7.5	-7 " 7	30 slugs
12 " "	-18 " 15.3	-6 " 6	
13 " "	-7.5" 7.5	-7 " 7	30 slugs
13 " "	-18 " 15.3	-3 " 3	
14 " "	-7.5 " 7.5	-7 " 7	30 slugs
15 " "	" " "	" " "	" "
16 " "	" " "	-5 " 5	" "
17 " "	" " "	-4 " 4	" "
0 " "	-18 " 15.3	-10 " 10	
-1 " "	" " "	-10 " 10	
-2 " "	" " "	-10 " 10	
-3 " "	" " "	-9 " 9	
-4 " "	" " "	" " "	
-5 " "	" " "	-8 " 8	
-6 " "	" " "	-7 " 7	
-7 " "	-16.25" 16.25	-6 " 6	65 slugs
-7 " "	-18 " 15.3	-5 " 5	
-8 " "	-16.25" 16.25	-5 " 5	65 slugs
-8 " "	-18 " 15.3	-3 " 3	
-9 " "	-16.25" 16.25	-1 " 1	65 slugs

Loading Diagram of Charging Face

X's indicate boundaries of 30 slug stringers
O's indicate boundaries of 65 slug stringers



2/3/44 Loading